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WIND TUNNEL PRESSURE MEASURING TECHNIQUES

D.S. Bynum, R.L. Ledford, and W.E. Smotherman

ARO, Inc.

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NOTICES

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FOREWORD

The work was sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65401F. The work was done in 1969-70 by personnel of ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC under Contract F40600-71-C-0002. The manuscript was submitted for publication on July 9, 1970.

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This technical report has been reviewed and is approved.

Hans K. Doetsch
Research and Development Division
Directorate of Technology

Harry L. Maynard
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ABSTRACT

This report gives those unacquainted with modern wind tunnel pressure measuring techniques and equipment a broad view of the topic and provides sufficient references so that additional information may be easily obtained. The material covered is limited to direct pressure measurements, i. e., force per unit area, and does not present techniques that determine pressure through its relationship to other measured parameters. Transducers, signal conditioning, data recording equipment, and static and dynamic calibrations are described.

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TABLES

ILLUSTRATIONS

SYMBOLS

a	Speed of sound, ft/sec (subscripts indicate particular region in shock tube, Fig. 83.)
A	Fraction of activity of partially active bridge legs, output of bridge relative to output without shunt balance network
b	Volume per millimeter length of capillary in McLeod gage, cm^3/mm
B	Attenuation of transducer output due to shunting effect of balancing network
C	Capacitance, farads or picofarads
C_A	Amplifier input capacitance, farads
C_C	Cable capacitance, farads
C_F	Charge amplifier feed-back capacitance, farads
C_T	Transducer capacitance, farads
d	Diameter, cm
d_1	Diameter of first tube in composite tubing system, in.
d_i	Diameter of other tubes in composite tubing system, in.
e	Base of natural logarithm
e	Electrical potential or voltage, volts
e_1	Transducer zero output voltage, volts
e_2	Balancing voltage added by voltage bucking network, or output voltage from reciprocity calibration, volts
e_{2_1}, e_{2_2}	Output voltages from reciprocity calibrations, volts
e_c	Capacitor voltage, volts
e_o	Bridge circuit output voltage, net output voltage from bucking balance network and bridge, $e_o = e_1 + e_2$, volts
$e(t)$	Voltage as a function of time
e_y	Voltage across bridge circuit load resistor
E_o	Charge amplifier output voltage, volts
E_s	Transducer equivalent voltage generator output, volts
$E(\omega)$	Fourier transform of the pressure system output voltage
f	Frequency, Hz
f_n	Resonant frequency, Hz
g	Local acceleration due to gravity, ft/sec^2 or cm/sec^2, ratio of acceleration to local acceleration due to gravity
g_c	Conversion factor, 1.333
h	Ratio of actual damping to critical damping; or height of liquid manometer or McLeod gage column, in., cm, mm
H	Number of active halves of a bridge
$H(\omega)$	Fourier transform of the pressure measuring system transfer function
i	Electric current, amp
i_y	Electric current through bridge load resistance, amp
j	$\sqrt{-1}$
K	Constant for reciprocity calibration, 10^7 for cgs units
$Kn_{w,i,d}$	Knudsen number based on wall temperature, indicated pressure, and orifice diameter
ℓ	Length of tube, ft, cm
ℓ_1	Length of first tube in composite tubing system, cm
ℓ_e	Effective length of composite tubing system, cm
ℓ_i	Length of other tubes in composite tubing system, cm
L	Length, inches or feet; number of analog inputs
L_1	Length of shock tube driver, ft

ΔL	Change in length, in.
M	Molecular weight, Mach number; number of groups of low level inputs
M_s	Shock Mach number
n	Number of pressure ports
N	Number of A-to-D converters
p	Pressure; psi, in. of water, in. of Hg, cm of Hg, mmHg, μ of Hg, decibels (db) based on 0.0002 dyne/cm^2, μbars
p_1	Pressure at end of tube (known), shock tube driven tube initial pressure, pressure input to McLeod gage or liquid manometer
p_2	Pressure at end of tube (unknown), pressure input to liquid manometer, pressure in region two of shock tube operation
p_5	Pressure in region five of shock tube operation
p_a	Ambient pressure in reciprocity calibrator
p_b	Model base pressure
$(p_i)_{d \to 0}$	Pressure measured with orifice as diameter approaches zero, lbf/ft^2
p_o	Wind tunnel stilling chamber pressure, initial pressure in tubing system
p_o'	Wind tunnel pitot pressure
$p(t)$	Pressure as a function of time
p_w	Wind tunnel wall pressure, true normal force per unit area exerted by a gas, lbf/ft^2
p_∞	Wind tunnel free-stream pressure
Δp_2, Δp_{side}	Pressure rise on shock tube side wall as shock wave passes
Δp_5, Δp_{end}	Pressure rise on end of shock tube as shock wave reflects
$P(\omega)$	Fourier transform of the pressure input function
$\dot{q}$	Heat flux, ft-lbf/ft^2-sec
Q_s	Charge from piezoelectric transducer, picocoulombs
R	Electrical resistance, ohms; universal gas constant, $\frac{\text{ft-lbf}}{\text{slug °K}}$
R_1	Resistance of top portion of bridge balance circuit potentiometer
R_2	Resistance of bottom portion of bridge balance potentiometer
R_3	$(R_1 + R_2)$ total resistance of bridge balance potentiometer
R_4	Resistance of bridge balance potentiometer wiper series resistor
R_5	$R_1 + 2R_4$ or $R_2 + 2R_4$
R_6 & R_7	Divider resistor in voltage bucking balance network
R_a	Transducer input resistance
R_A	Amplifier input resistance
R_c	Resistance of bridge circuit shunt
R_L	Transmission line resistance
R_o	Transducer output resistance
R_p	Transducer input pad resistance
R_y	Bridge circuit load resistance
ΔR	Change in bridge leg resistance
S_1, S_2	Sensitivities of transducers from reciprocity calibration
t	Time; sec, msec, μsec
t_i	Time required to travel between two pressure ports on a pressure switch
t_o	Initial rise time of a pressure switching system without a volume
t_{ov}	Initial rise time of a pressure switching system with a volume
t_p	Time to first peak of transducer response after step input
t_r	Time to record pressure at each position of a pressure switch
t_t	Rise time of pressure at each position of a pressure switch after the initial position

t_{tv}	Rise time of pressure at each position of a pressure switch with a volume after the initial position
T	Total time for a pressure switch to scan n ports, sec; nondimensionalized time $\frac{at}{L}$
T_1	Temperature at end of tube where pressure is known, °K
T_2	Temperature at end of tube where pressure is unknown, °K
T_D	Period of a square wave, sec
T_g	Temperature of gas molecules, °K
T_V	Total time for pressure switch with volume to scan n ports, sec
T_w	Surface temperature of model, °K
U_s	Shock wave speed, ft/sec
V	Bridge excitation voltage, volts; volume of tubing and measuring transducer, cm^3; initial volume of McLeod gage gas sample, cm^3
V_1	Voltage across voltage bucking balance bridge
V_2	Excitation voltage for voltage bucking balance networks
x	Distance, ft
α	Thermal accommodation coefficient
β	Cathode follower gain
γ	Ratio of specific heats (1.4 for air), subscripts (1, 2, 3) indicate region of shock tube operation, Fig. 83
λ	Wavelength of radio telemetry signal, m
ϵ	Unit strain, in./in.
μ	Viscosity, poises
ξ	Shock strength, p_1/p_2
ρ	Density, gm/cm^3
τ	Time constant, sec
ω	Angular frequency, radians/sec

ABBREVIATIONS

AEDC	Arnold Engineering Development Center, Arnold Air Force Station, Tennessee 37389
AC	Alternating current
A-to-D	Analog-to-digital
BRL	Ballistics Research Laboratory, Aberdeen Proving Ground, Maryland 21005
cm	Centimeter
CAL	Cornell Aeronautical Laboratory, P. O. Box 235, 4455 Genessee Street, Buffalo, New York 14221
CEC	Consolidated Electrodynamics Corporation, 360 Sierra Madre Villa, Pasadena, California 91109
CVC	Consolidated Vacuum Corporation, Rochester, New York
DC	Direct current
FET	Field effect transistor
FM	Frequency modulation
F.S.	Full scale
ft	Foot
Hz	Hertz, cycles per second
ISA	Instrument Society of America, Penn-Sheraton Hotel, 530 William Penn Place, Pittsburgh, Pennsylvania 15219
JPL	Jet Propulsion Laboratory, Pasadena, California
kHz	Kilohertz, thousands of cycles per second
kΩ	Kilohms

LVDT	Linear variable differential transformer
mmHg	Millimeters of mercury
MHz	Megahertz, millions of cycles per second
MΩ	Megohms
NBS	U. S. National Bureau of Standards, Washington, D. C. 20234
NOL	Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland 20910
NPL	National Physical Laboratory, Teddington, Middlesex, England
pF	Picofarads, 10^{-12} farads
psi	Pounds per square inch
psid	Pounds per square inch differential
RAE	Royal Aircraft Establishment, Ministry of Technology, Bedford, England
RF	Radio frequency
®	Registered trademark
VKF	von Kármán Gas Dynamics Facility, AEDC
VR	Variable reluctance
μ	Micro, 10^{-6}
μHg	Microns of mercury, 10^{-6} meters of mercury

1. INTRODUCTION

Pressure measurements in wind tunnels are of interest not only for determining the pressure distribution on aerodynamic shapes but also for determining test conditions in the wind tunnel test section. Up to about fifteen to twenty years ago, the majority of wind tunnel pressures were measured with liquid manometers, for the most part manually read. Some automated manometers were built, and some are still being used. However, liquid manometers lacked the fast response, high and low pressure capability, and amenability to automation required for pulsed and high speed wind tunnels. The liquid manometer has been replaced to a large extent by electro-mechanical transducers with automated data recording systems.

The purpose of this AGARDograph is to present a description of basic modern equipment and techniques available for wind tunnel pressure measurements. The purpose is not, however, to present the most sophisticated systems. This report is not intended for the experts in the wind tunnel pressure measuring field but for those who are not intimately acquainted with the state-of-the-art. Abundant references are included to help the reader in finding more complete details of pressure measuring and calibration equipment and techniques. Also included is a general bibliography of references not directly connected to the text but which are pertinent to the subject.

The range of pressures which can be encountered in a wind tunnel can be quite large, especially at high Mach numbers and altitudes. Figure 1 shows the location of some of the extremes in pressures which can be expected in wind tunnels. The maximum pressure is obviously p_o, the reservoir or stilling chamber pressure. The wall pressure, p_w, can take on any value from p_o near the stilling chamber to approximately p_∞, the free-stream pressure, at the test section. The pitot pressure, p_o', is generally the maximum value of pressure encountered in the test section. However, the pitot pressure in the vicinity of a ramp can be considerably higher than p_o' in high Mach number wind tunnels. The base pressure, p_b, is generally the lowest pressure to be measured and will be on the order of the free-stream pressure, p_∞. Approximate values of p_o, p_o', and p_∞ can be predicted from Figs. 2 and 3 if the altitude simulation and Mach number are known. Figure 2 was plotted from 1962 U. S. Standard Atmosphere data from (1)*; however, for the purpose here, a straight line approximation would have been adequate. The data in Fig. 3 are for perfect or ideal air (2). Therefore, the ratio p_o'/p_∞ is in slight error because of real gas effects at high Mach numbers. The ratio of p_o/p_∞ can be in error as much as a factor of two (high or low depending on the value of temperature and pressure), at the higher Mach numbers because of the departure of actual nozzle flow from the perfect gas situation (3).

In addition to the range of pressures to be measured, frequency and time response requirements are a consideration. Frequently, aerodynamicists are interested in the periodic pressure fluctuation as well as the steady pressure in continuous flow wind tunnels. These periodic pressures are generally low compared to the steady pressure and can be as high as the 100-kHz range in frequency. Intermittent (blowdown) and pulsed (pulsed arc heated, gun tunnels, shock tunnels, shock tubes, etc.) wind tunnels require the pressure measuring system to respond to the transient nature of the pressures. This can require rise times to a step pressure of from a few seconds to less than 100 μsec.

Unfortunately, environmental effects other than pressure are frequently applied to the measuring system in the wind tunnels. Among the more troublesome of these are heat flux and vibration which can present a difficult problem if the pressure measuring devices are located wholly or in part in the wind tunnel model or on the wind tunnel wall.

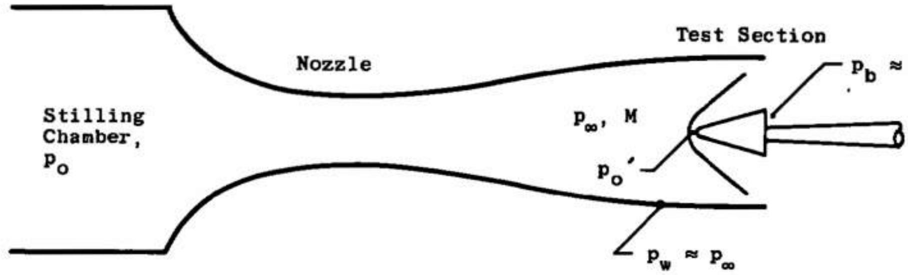

Fig. 1 Location of Extreme Pressures in a Typical Wind Tunnel

*Numbers in parentheses denote reference numbers.

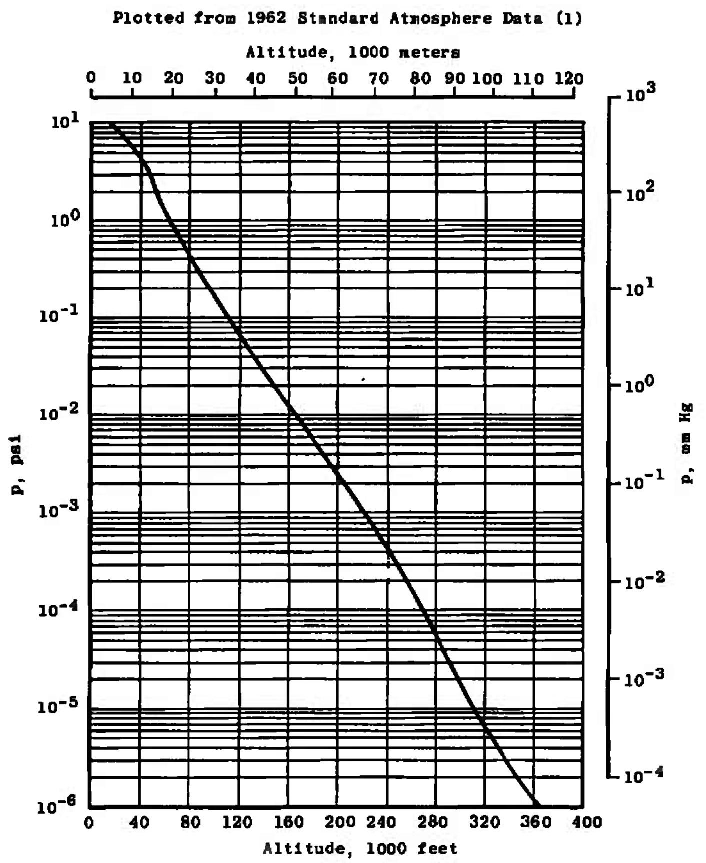

Fig. 2 Atmospheric Pressure versus Altitude

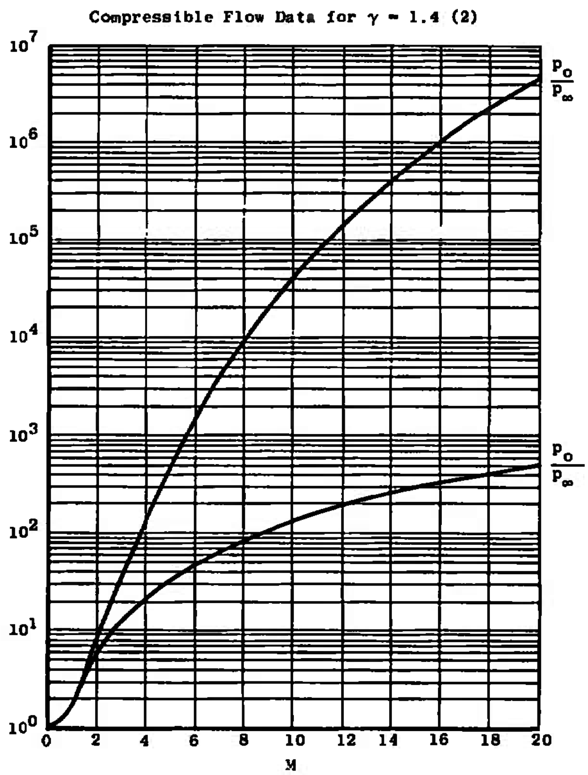

Fig. 3 Perfect Air Pressure Ratios versus Mach Number

2. TRANSDUCERS

Wind tunnel pressure measurements are most frequently accomplished by use of transducers. For the purposes of this publication, a transducer will be defined as a device which provides an electrical output signal for a physical quantity (pressure) input, whether or not auxiliary energy is required. This output signal may be measured, stored, or manipulated in other ways by the use of electronic signal conditioning equipment (see Section 3.2).

Pressures from 2×10^{-7} psia to approximately 100,000 psi are successfully measured in wind tunnel tests with the aid of elastic-type transducers whose electrical output signal emanates from the deflection or deformation caused by a pressure activated sensing element. The most common types of elastic sensing elements are diaphragms (plates and membranes), bourdon tubes, bellows, vessels, and capsules. In order to produce an electrical signal, these elastic elements operate in conjunction with electrical sensing elements which provide an electrical change in response to the deflection or deformation of the elastic element. The most frequently used electrical sensing elements include potentiometers, metallic and semiconductor strain gages, variable reluctance devices, differential transformers, piezoelectric elements, and variable capacitance devices.

The confines of this publication, obviously, do not permit a thorough and detailed treatment of all types of pressure transducers employed in wind tunnel testing. The effort should, however, provide a general understanding of the most common types of transducers, along with references which will allow the interested reader to study further the theory and other details of the instruments. The commercial availability of the pressure transducers will not be presented in this undertaking, but such information may be found in the ISA "Transducer Compendium" (4). This source includes many manufacturers and provides pertinent transducer characteristics which will aid the prospective buyer in obtaining an applicable instrument.

A summary of the general performance characteristics of the major types of pressure transducers is given in Table I.

TABLE I
SUMMARY OF TYPICAL TRANSDUCER CAPABILITIES

Transducer Type	Pressure Measurement Range	Nominal Operating Temperature Range	Nominal Temperature Sensitivity	Resonant Frequency	Acceleration Sensitivity
Variable Resistance	10^{-4} to 100,000 psi	-430 to 300°F -55 to +250°F**	0.25% F.S. per 100°F 2% F.S. per 100°F**	Up to 1 MHz	From 0.001% to 1% F.S. per g
Variable Reluctance	3×10^{-5} to 10,000 psi	-65 to +250°F	2.0% F.S. per 100°F	Up to 25 kHz	From 0.0005% to 1.0% F.S. per g
Variable Capacitance	2×10^{-7} to 10,000 psi	-55 to +225°F	1.0% F.S. per 100°F	Up to 300 kHz*	From 0.0001% to 0.5% F.S. per g
Piezoelectric	5×10^{-4} to 100,000 psi	-400 to +500°F	1% to 5% F.S. per 100°F	Up to 500 kHz*	From 0.0005 psi per g to 0.1 psi per g
Force Balance	1.5 to 10,000 psi	-40 to +165°F	1.5% F.S. per 100°F	See Note 1	10% F.S. per g

*Does not include bar-type gages which may have rise times as low as 0.1 μsec
**Potentiometric Transducers

Note 1 Response time to 98% final value for a step pressure input ranges from 0.1 to 1.0 sec.

2.1 Variable Resistance Transducers

The majority of variable resistance transducers may be listed in two categories: transducers which provide large resistance changes that normally operate in potentiometer circuits, and transducers with small resistance changes which are usually employed in bridge circuits. The most prominent differences in these two types of devices are found in the areas of resolution and noise generation as well as sensitivity. These characteristics along with others will be discussed for some of the more common potentiometer and strain-gage-type transducer designs.

2.1.1 Potentiometric Pressure Transducers

2.1.1.1 Principle of Operation

The basic operating principle of the potentiometric pressure transducer is presented in Fig. 4. The device consists of three main components: the force collector, the sliding contact wiper, and the resistance wire winding or other type resistance element. The pressure to be measured is applied to the force collector (capsule) which, through a linkage rod, moves a sliding contact (wiper) across the electrical

resistance wire windings. This action provides a resistance change between the wiper signal lead and an excitation lead. Hence, with the wire winding excited as shown, a voltage change between the wiper and excitation lead can be realized. For most transducer designs, this change is linear, but sine, logarithmic, and other functions may be obtained by proper components and assembly techniques. More detailed treatments of the potentiometric transducer theory are presented by Neubert (5), Dummer (6), and Norton (7).

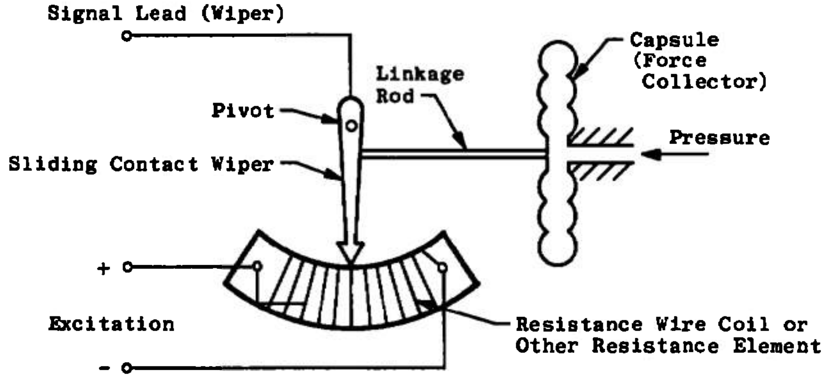

Fig. 4 Potentiometric Pressure Transducer Schematic

The force-summing members (or elastic elements) most frequently used in the construction of these transducers include capsules and bourdon tubes as shown in Fig. 5. Capsule elements are normally used for pressure ranges up to approximately 300 psi. These elements consist of two die-stamped, dish-shaped, corrugated diaphragms of spring alloy attached at the outer circumference. Materials commonly employed in capsules include Inconel-X®*, phosphor bronze, and NI-Span-C®**. The latter is most widely used because of its temperature stability characteristics. Additional information concerning capsule characteristics may be found in (8), (9), (10), and (11). Reference (12) is especially helpful as it describes many transducing techniques including capsules.

In a typical design, pressure is admitted into the capsule through a port in one of the diaphragms. A linkage rod is attached to the center of the opposite diaphragm so that the diaphragm deflection (caused by the pressure application) moves the linkage rod in the direction shown in Fig. 5. A nominal full-scale deflection for such a system is two percent of the capsule diameter. In order to obtain large deflections, two or more capsules may be cascaded so as to add the deflections of each.

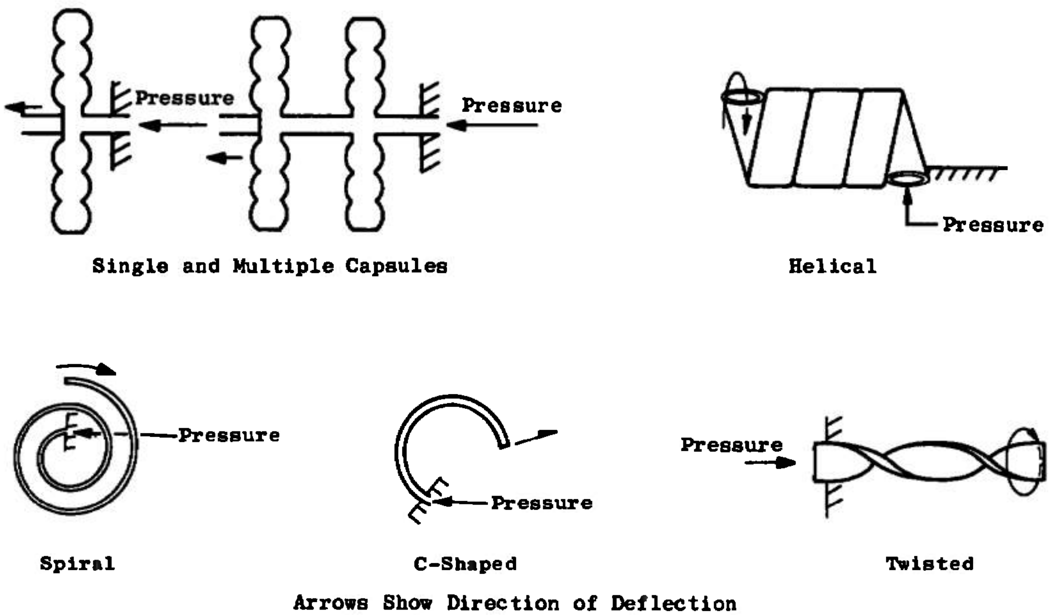

Fig. 5 Potentiometric Transducer Force-Summing Members

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*Trademark International Nickel Co.

**Trademark H. A. Wilson Co.

The bourdon tube is a spring alloy tube with an elliptical cross section which is closed at one end and is shaped in a curved or twisted configuration as shown in Fig. 5. When pressure is admitted into the tube, the difference in area exposed to the pressure causes the curved tube to tend to straighten. Hence, if the open end is held securely, the closed end will move. The bourdon tubes can generally provide greater deflections than capsules as Neubert (5) shows that C-shaped (Fig. 5) tubes of 2-in. bending diameter have a useful travel of about 0.125 in. Ni-Span-C® alloy is the most popular bourdon tube material because of its temperature stability. Further studies on the deflections and characteristics of these tubes are available in (12), (13), (14), and (15).

Many transducer designs incorporate the spiral, helical, and C-shaped bourdon tubes because of their large deflections which in some cases permit transducers to be built without an extra linkage between the tube and the resistance element. This minimizes vibration, friction, and backlash problems. Twisted bourdon tubes provide less deflection, and their application is generally restricted to the higher pressure range potentiometric transducers.

The resistance element of a potentiometric transducer most frequently consists of electrical wire wound on a mandrel. The wire is generally a platinum alloy on the order of 0.001-in. diameter, whereas the mandrel is an insulating material such as ceramic, phenolic, etc. For a detailed treatment of this type of resistance element, see Dummer (6). Although the wirewound elements are more common, other elements such as carbon-film and conductive-epoxy have recently found application in the potentiometric transducer field. These elements offer improved resolution and may be fabricated in much smaller configurations. Smooth surfaces are also provided, and this lends to better noise and vibration characteristics.

2.1.1.2 Performance

Potentiometric transducers, especially those employing wire winding resistance elements, are hampered by resolution and noise problems. As the wiper moves across the windings, a step resistance change (5) is generated when the wiper disconnects with one winding or makes contact with another. The amplitude of this step change, and hence the resolution, depends mainly upon the geometry of the wire windings and wiper. A nominal value of resolution for most potentiometric transducers is 0.2 percent of full scale.

Electrical noise is also generated because of contact resistance variations as the wiper travels over the resistance element. The variations are generally caused by contact pressure fluctuations and particle contamination at the wiper-wire contact. This noise generation tends to increase with the life of the instrument because of wear and misalignment of the wiper and track. Noise spikes may also be caused by vibrations which tend to lift the wiper from the resistance element. Any linkages required in the transducing system will cause the instrument to be more sensitive to vibration. A frequently used method of reducing the harmful effects of vibration is oil damping on the linkages and elastic elements. The damping fluid (usually silicone oil) surrounds the entire transducing configuration. Recent transducer designs have pushed the vibration survival capability to 50 g.

Because of the relatively low mechanical resonant frequency and large internal volume, the potentiometric transducers are generally not considered for dynamic measurements. The large physical size (on the order of 1.5-in. diameter by 3 in. long) of these instruments is undesirable for many applications. Full-scale pressure ranges from 0.5 to 20,000 psi are available, and differential, gage, and absolute pressure configuration are provided. Potentiometric transducers with a static error band (4) (the error band applicable at room conditions and in the absence of vibration, shock, etc.) of 0.3 to 0.5 percent of full scale are common. These instruments are normally built to operate in a temperature range from -65 to +250°F with a nominal temperature sensitivity of approximately 0.02 percent per °F. Probably the most outstanding feature of the potentiometric transducer is its high electrical output, since resistance changes as large as 100 KΩ per psi (4) may be obtained. The performance characteristics as well as the availability and cost of many potentiometric transducers are furnished in the ISA "Transducer Compendium" (4).

In summary, it may be said that the general application regime of the potentiometric transducer involves areas of low acceleration for the measurement of static pressures where extremely high electrical output is required.

2.1.2 Strain-Gage Pressure Transducers

With strain-gage pressure transducers, a pressure change is converted into a change in resistance caused by the strain in a strain gage or gages. Most strain-gage pressure transducers incorporate four active strain-gage elements and a typical application is given in Fig. 6. This is the so-called bonded strain-gage technique and consists of four gages bonded to the elastic element (cantilever). When a force is applied as shown, the two top strain gages (Gages 1 and 2) are in tension and increase in resistance while the bottom elements (Gages 3 and 4) are in compression and decrease in resistance. By connecting the two elements whose resistance increases (Gages 1 and 2) and the two whose resistance decreases (Gages 3 and 4) in diagonally opposite arms of a bridge as shown in Fig. 6, maximum output is obtained. In some transducer designs only one or two active strain gages are employed, and the bridge configuration is completed by dummy (inactive) strain gages or fixed resistors.

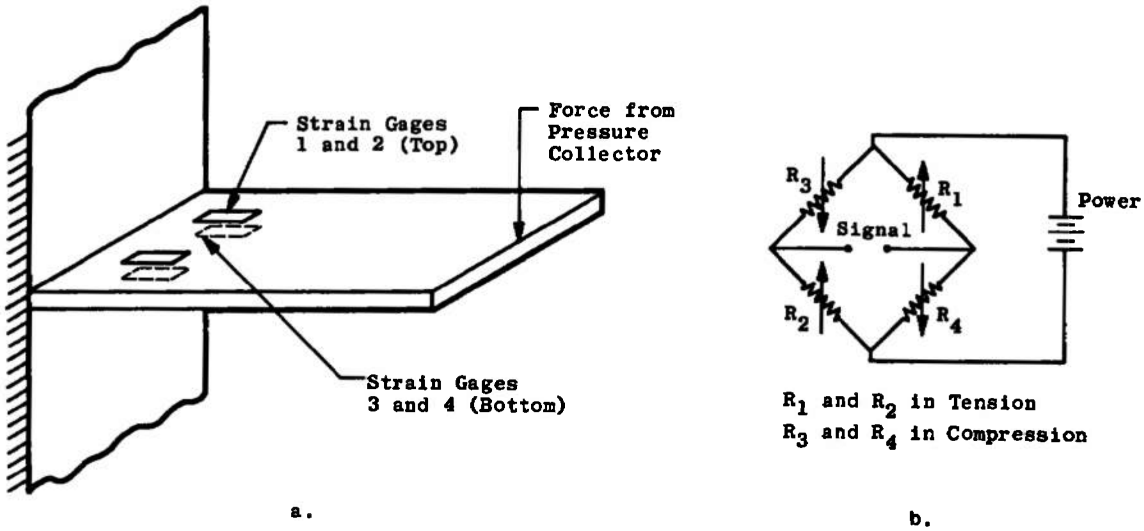


Fig. 6 Bonded Strain-Gage Sensing Configuration

The most common types of strain gages are small wire, metal foil, and semiconductor. The theory, construction, and application of these various strain-gage configurations are adequately treated in (7), (16), (17), (18), (19), (20), (21), and (22). In recent years, the use of wire strain gages has substantially decreased because of the advantages offered by the foil and semiconductor types. The foil and semiconductor types are manufactured in smaller configurations which permit the design of miniature, high frequency transducers. Semiconductor gages 0.040 in. long by 0.010 in. wide and etched foil gages 0.100 in. long by 0.020 in. wide are available, and resistance values ranging from 120 to 5000 ohms are common for both types. The semiconductor gages offer an outstanding advantage over metal gages (wire and foil) as their gage factor is approximately 75 times greater. The gage factor is defined as the ratio of the normalized gage resistance change to the mechanical unit strain in the gage $\left(\frac{\Delta R}{R} / \frac{\Delta L}{L}\right)$. The advent of the semiconductor strain gage has made possible the development of small and extremely stiff pressure sensors, permitting high frequency dynamic measurements to be made more conveniently and more accurately. Because of the higher output, the higher stiffness sensors may be used down to a smaller percentage of the full-scale range. This "rangeability" may be used to reduce the number of different transducer ranges required to investigate a wide pressure regime.

Methods for temperature compensating metal strain-gage (wire and foil) transducers over a temperature range from -430 to +300°F for both zero drift and sensitivity change have been devised and are described in (5), (16), (23), and (24). In late 1958, when semiconductor strain gages were first being used in transducer construction, problems were encountered that were attributable to the temperature characteristics of the elements. The change in gage factor with temperature ranges from 1%/100°F to almost 20%/100°F, whereas the temperature coefficient of resistance varies from 3%/100°F to 20%/100°F. This wide range of characteristics led to the development of temperature compensation techniques somewhat different from those normally employed for metal strain gages. These techniques, described in (25), (26), and (27) provide semiconductor-type transducers with temperature characteristics comparable to those of metal gages.

Strain gages (wire, foil, and semiconductor) are bonded to the pressure sensing member by the use of adhesives. There are several different adhesives and application techniques available, and the strain-gage supplier normally furnishes the necessary installation information. References (28) and (29) treat this subject in detail.

2.1.2.1 Gaged Diaphragm Pressure Transducers

One of the most convenient applications of bonded strain gages for the measurement of pressure is a diaphragm with the strain gages bonded directly to the surface as shown in Fig. 7. A diaphragm (12) is essentially a thin circular plate fastened (usually welded or soldered) around its periphery to a support shell. Frequently used diaphragm materials include several types of stainless steel and beryllium copper. When pressure is applied to one of the surfaces, the diaphragm deflects in accordance with the theories presented in (30) and (31). The gaged diaphragm element is useful in areas of high acceleration, since only one moving part (diaphragm) is involved, and hence the seismic mass is small. Although this type sensor is of simple construction, an inherent problem is present. Neubert (5) has shown that nonlinearity can exist if the proper relationship between the diaphragm thickness, diaphragm diameter, and pressure range is not established. However, Neubert (5) presents data which can be used to design around this problem.

If strain gages are located on a diaphragm as shown in Fig. 7, elements 1 and 2 will be in tension while 3 and 4 will be in compression. By electrically connecting these gages as shown in Fig. 7d, a fully active bridge is realized.

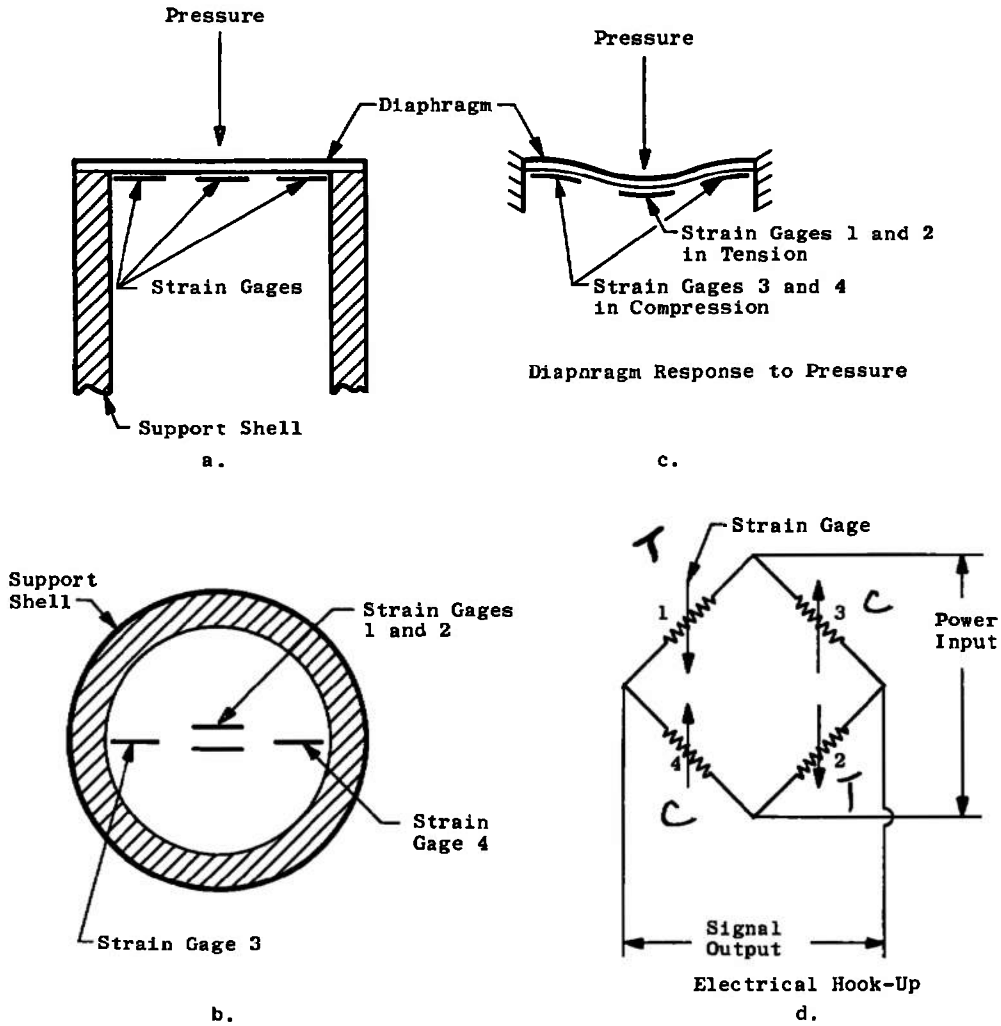


Fig. 7 Gaged Diaphragm Transducer

If a diaphragm is attached at the end of a tube or case, as in Fig. 7a, a so-called flush diaphragm transducer exists. This is a valuable instrument for fast time-response measurements frequently required in wind tunnel tests. With the transducer diaphragm located flush with a model surface or tunnel wall, the time lag attributable to tube lengths (see Section 3. 1) or other pneumatic configurations is minimized. This arrangement does, however, render the transducer more susceptible to temperature effects and damage from flow contamination. A further discussion of this problem can be found in Section 3.1.1. In measurement areas where fast response times are not required, the diaphragm may be placed down inside a case, and hence the sensing element is afforded some protection from the measurement environment.

Rogers (32) discusses the design and performance of a flush-diaphragm-type transducer used for surface pressure measurements. This instrument employs semiconductor strain gages and is only 0. 25 in. in diameter by 0. 025 in. thick. A unique diaphragm-type transducer is described by Clements, Wood, Weisblatt, and Pallone (33). The device is 0. 100 in. in diameter and employs a 0. 00025-in.-thick diaphragm with a bonded platinum-rhodium wire strain gage and is reported to measure pressures down to 10^{-4} psi.

Gaged diaphragm pressure transducers utilizing vacuum deposited metal strain gages are commercially available. These instruments are fabricated by depositing an electrical insulating film on the diaphragm surface and then depositing the four metal film strain gages onto the film. This technique permits the fabrication of transducers smaller than those normally possible with conventional foil gages and also eliminates the problems associated with the strain-gage adhesives.

Recent advances in the semiconductor field have led to the development of a monolithic integrated circuit Wheatstone bridge consisting of the four strain sensitive resistive arms formed directly on a silicone diaphragm. These devices, as reported by Kurtz and Gravel (34), represent a significant state-of-the-art advancement in miniaturization, as flush diaphragm pressure transducers with a diameter of 0.070 in. (35) have been fabricated using such diaphragms. Their inherent high natural frequency (≈1 MHz) and high output make them ideal for dynamic measurements where point pressure profiles are required.

2.1.2.2 Cantilever-Type Transducers

This type of bonded strain-gage transducer consists essentially of a pressure collecting element which, through a linkage rod, transmits its force to a cantilever instrumented with strain gages. The pressure collecting elements most frequently used are diaphragms [flat (12, 30, 31), and corrugated (12, 36)], capsules (9, 12, 36), and bellows (12, 37). The cantilever stiffness should be high in comparison with that of the pressure collector to minimize the effects of hysteresis, nonlinearity, and instability of the latter. Some practical arrangements of cantilever-type pressure transducers are given in Fig. 8. Four strain gages are bonded to the cantilever in the configuration shown in Figs. 6 and 8c and electrically connected as shown in Fig. 8d. Because of the strain characteristics of a cantilever (31), transducers of this type may be successfully employed for the measurement of low pressure, as full-scale pressure ranges as low as 0.1 psi are available. However, the resonant frequency (38) is relatively low because of the combined stiffness and mass of the pressure collector-linkage rod-cantilever system, and consequently the acceleration sensitivity is high. A large number of these transducers incorporate tubing, fittings, or other pneumatic configurations for the pressure input, and this renders the devices inadequate for many dynamic measurement (Section 3.1.2) requirements.

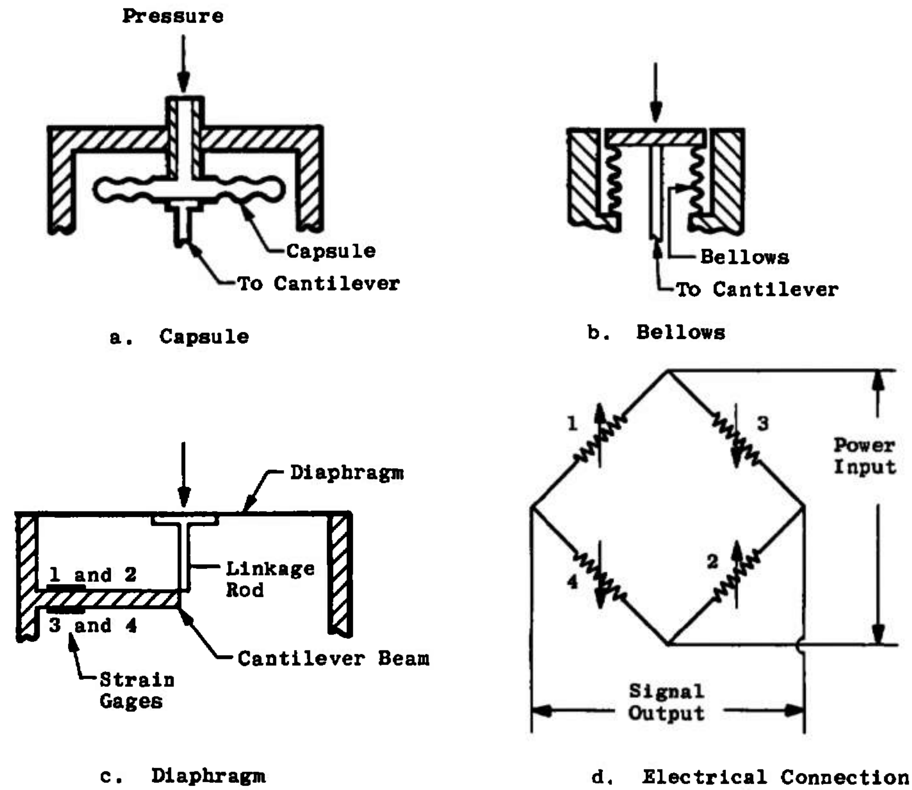


Fig. 8 Bonded Strain-Gage Cantilever Transducer Configurations

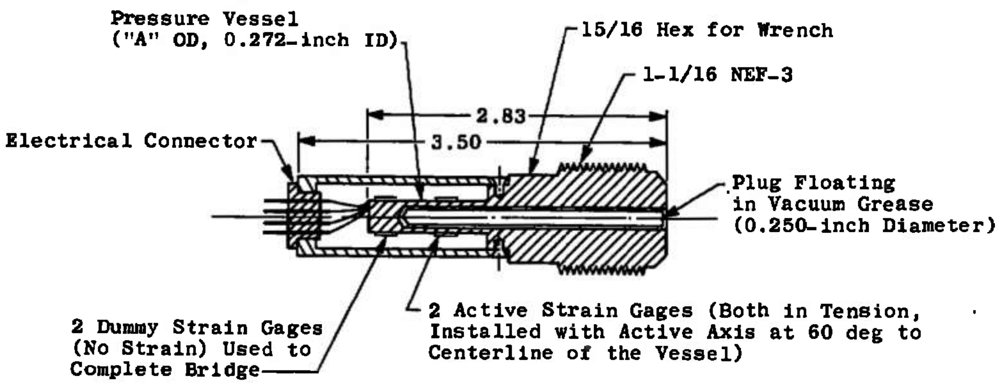
Painter (39) describes a diaphragm-cantilever-type transducer designed to measure pressures from 0 to 0.1 psi. The instrument utilizes semiconductor strain gages and has a resonant frequency of approximately 1500 Hz. A cantilever-type transducer, employing a rubber diaphragm, for the measurement of from 0 to 0.1 psi is discussed in (40). This device also uses semiconductor strain gages but is smaller (0.500 in. in diameter by 0.230 in. thick) than the transducer presented by Painter (39). An instrument utilizing a metal bellows which activates a bonded wire strain-gage cantilever sensor is described by Kolb and Szczepanik (41). This transducer is relatively large (2.5 in. in diameter by 2.5 in. long) and is designed to measure pressures up to 15 psi.

Cantilever beams with integral strain gages (35) are also available. They consist of monocrystalline silicon to which the semiconductor stress sensors are atomically bonded using techniques (34) of solid state diffusion and/or epitaxial growth. The four strain sensors are an integral and inseparable part of

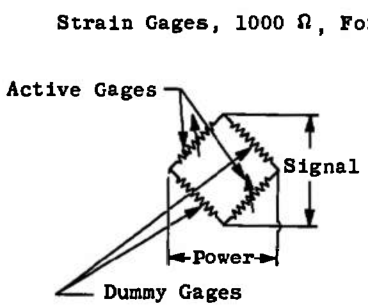
the silicon substrate, and hence the problems common with bonding adhesives are eliminated. The strain sensors are located on the silicon cantilever beam as shown in Figs. 6 and 8 so as to provide the full bridge configuration of Fig. 6b or 8d. Beams as small as 0.100 in. long by 0.022 in. wide by 0.001 in. thick are available and may be used in conjunction with diaphragms, bellows, etc., to provide the transducing systems shown on Fig. 8. These cantilevers permit the construction of small transducers and also provide the advantage of the high sensitivity semiconductor strain sensors.

2.1.2.3 Pressure Vessel Transducers

Wind tunnel test pressures ranging from approximately 1000 to upwards of 100,000 psi may be measured with transducers employing the pressure vessel technique. The pressure vessel (Fig. 9) consists of a cylindrical tube with one end closed while the other is open to receive the pressure to be measured. With pressure applied to the inside of the tube, a barrel or hoop strain is provided at the outside circumference according to the theory of (42). Two strain gages are bonded around this outside circumference to detect the hoop tension while two identical elements are bonded to the solid end of the structure where little or no strain is present. The two-hoop tension gages are usually located with their axis 60 deg off the axis of the cylinder so as to sense not only the hoop tension but also the longitudinal tension. By connecting the four strain gages as shown in Fig. 9b, a full bridge two-active-arm configuration, with its inherent temperature compensating characteristics, is obtained.



(a)



(b)

"A", inches	Pressure* Range, psi
0.332	10,000
0.384	20,000
0.430	30,000
0.510	50,000

*Based on 20,000-psi Stress under the Active Gages

Fig. 9 Pressure Vessel Type Transducer

A transducer of this type (Fig. 9) has been successfully employed at the AEDC. The vessel cavity is filled by a metal plug floating in vacuum grease. This configuration provides thermal isolation between the flow medium and the strain gages. The transducer is built in pressure ranges from 10,000 to 50,000 psi, and both metal foil and semiconductor strain gages are used as dictated by the application requirements. Two notable disadvantages of this type transducer are that it is limited to the measurement of high pressures and its large mass which lends to relatively high acceleration sensitivity.

2.1.2.4 Embedded Strain-Gage Transducers

The basic configuration of this type transducer consists of a strain gage embedded in a resin as shown in Fig. 10. When a uniaxial pressure is applied, a strain is transmitted through the epoxy resin to the strain gage which in turn provides a proportional resistance change. A transducer similar to this is described by Chiku and Igarashi (43). The instrument utilizes two semiconductor strain gages (one positive gage factor and one negative gage factor) connected in a half bridge. The transducer is extremely small (~0.035 in. in diameter) and is designed to measure pressures up to approximately 750 psi. The higher pressure range transducers generally employ a short length of manganin wire as the encapsulated strain gage. Such devices are discussed in (44) and (45). Keough (46) also describes a transducer

of this type designed for extremely fast time response (~ 0.25 μsec) which is capable of measuring pressures up to 200 kbars (3 x 10^6 psi). This high range capability is, however, not required in normal wind tunnel testing.

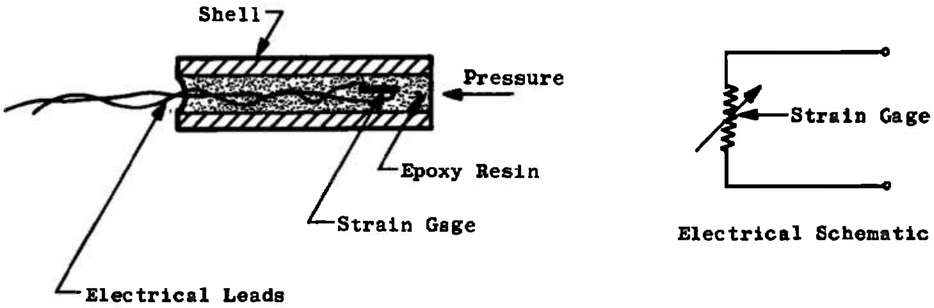


Fig. 10 Embedded Strain-Gage Transducer

The embedded strain-gage-type transducer is used infrequently, but is applied in high pressure areas where fast response is required since most of these transducers possess a rise time as low as 1 microsecond.

2.1.2.5 Unbonded Strain-Gage Pressure Transducers

The unbonded strain-gage transducer operates on basically the same principle as the bonded type (5, 47); that is, the electrical resistance of a wire or filament varies with strain changes. Wires or filaments are strung between electrical insulating pins - one on a fixed frame and one on a movable armature. The wires are installed under an initial tension and arranged as shown in Fig. 11a to form the four-active-arm, full bridge circuit of Fig. 11b. Under pressure the elastic element (usually a diaphragm or bellows) displaces the armature, causing filaments 1 and 2 to elongate (increase resistance) while 3 and 4 shorten (decrease resistance). The filaments are normally smaller than 0.001 in. in diameter and are made from many different materials of which most are nickel alloys.

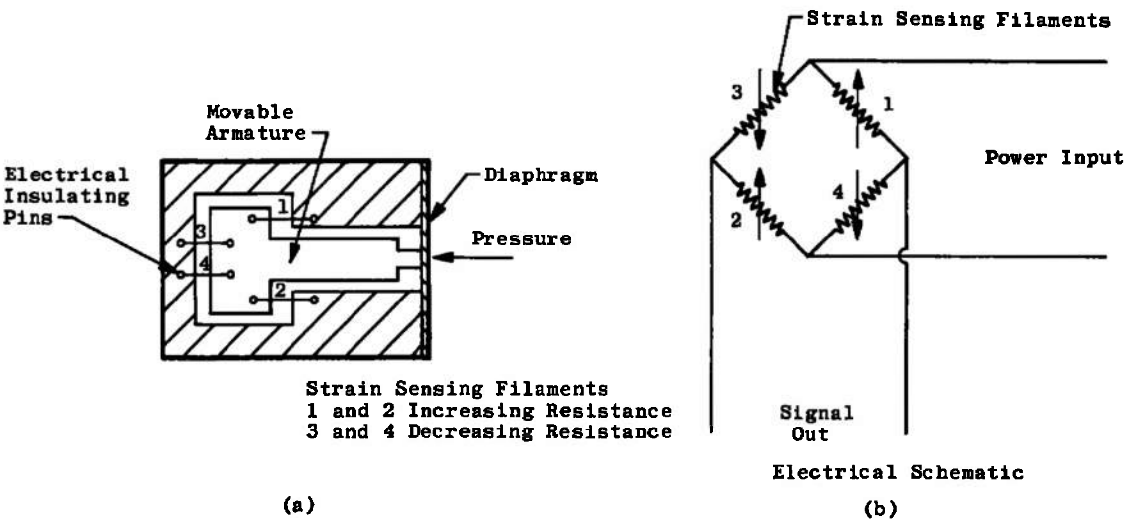


Fig. 11 Unbonded Strain-Gage Transducer

This type transducer is most effectively used for static pressure measurements since the relatively large mass of the armature does not permit high resonant frequency necessary for many dynamic applications. This large mass also hampers the usefulness of the transducer in areas of high acceleration. The unbonded strain-gage transducer is also limited by the low sensitivity (output) inherent for wire strain gages. Pressure ranges from 1 psi to approximately 100,000 psi are provided by this type instrument.

2.1.2.6 General Performance of Strain-Gage Pressure Transducers

The different types of strain-gage transducers discussed here provide combined performance characteristics adequate for many wind tunnel pressure measurement applications. The time response regime from static pressure to dynamic pressure (where flush-mounted instruments with resonant

frequencies of 1,000,000 Hz are adequate) is covered by this type transducer. Full-scale pressure ranges from 0 to 0.1 psi to 0 to 100,000 psi are provided, and static error bands as low as 0.1 percent of full scale are achieved in some models. Full scale outputs from ≈ 2 mv per volt excitation for metal strain gages to ≈ 200 mv per volt excitation for semiconductors are available. Temperature compensation techniques permit fabrication of transducers with temperature sensitivities as low as 0.25 percent of full scale per 100°F temperature change over a temperature range from -430 to 300°F. Acceleration and vibration errors are obviously different for various strain-gage transducers, but are especially low for the gaged diaphragm (Section 2.1.2.1) configuration. The other types are somewhat sensitive to acceleration, and in pressure ranges below 10 psi, errors of 0.5 percent of full scale per g are not uncommon. For more complete specifications of various commercially available strain-gage-type pressure transducers, the ISA "Transducer Compendium" (4) may be consulted.

2.2 Variable Reluctance Pressure Transducers

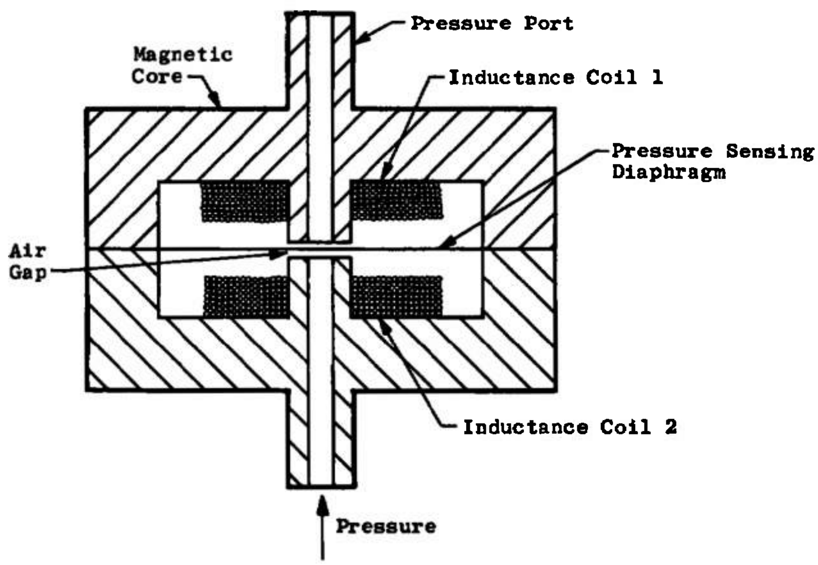
2.2.1 Diaphragm-Type Variable Reluctance Transducers

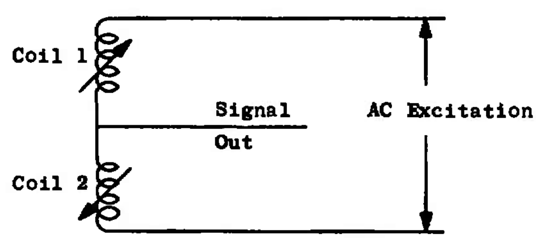
A variable reluctance (VR) pressure transducer commonly used for wind tunnel pressure measurements employs a diaphragm as the elastic element and is shown in simplified form in Fig. 12. A diaphragm of magnetic material, supported between two inductance core assemblies, completes a magnetic circuit with the cores. The diaphragm deflects (30, 31, and 48) when a differential pressure is applied to the pressure ports. This increases the air gap in the magnetic flux path of one core while decreasing the gap in the other; hence, the reluctance of each flux path is altered. The overall effect is a decrease in inductance of one of the wire wound coils and an increase in the other. If the two coils are connected as shown in Fig. 12, a half-bridge, two-active-arm device is formed and may be treated as discussed in Section 3.2.2. A more complete consideration of the theory and operation of this diaphragm-type variable reluctance device is given by Patterson (49).

Advantages offered by this type transducer are found in the areas of sensitivity and acceleration capabilities. Pressure sensitivities as high as one volt per psi are available, and pressures down to approximately 0.00003 psi may be measured. Because of the extremely low seismic mass (diaphragm only) of this sensing device, it is capable of withstanding high levels of acceleration. By proper orientation (diaphragm parallel to axis of acceleration) the effects of acceleration are minimized and the transducer may be effectively used to measure low pressures in an environment of moderate acceleration levels. These transducers are frequently built in miniature configurations (as small as 5/8 in. diameter) (50 and 51) which allows a number of the transducers to be employed in the small models required for many wind tunnel tests.

Because of the relatively low internal volume of most diaphragm-type VR transducers, many wind tunnel dynamic pressure measurements are successfully made by use of this instrument. However, response-time limitations are imposed by the pressure-inlet port configuration, especially at low absolute pressures (Section 3.1).

A major disadvantage of this transducer is its susceptibility to particle contamination. If the fluid contains particles, they may easily become lodged





Electrical Configuration

Fig. 12 Diaphragm-Type Variable Reluctance Pressure Transducer

in the small air gap (~ 0.001 in.) between the core and diaphragm and subsequently alter the performance of the instrument either by mechanical or magnetic interference. Another disadvantage is the electrical (inductive) characteristics which necessitate the use of AC excitation.

Smotherman, et al. (50 and 51), describe a transducer of this type which is built in several pressure ranges that permit the measurement of pressures from 0.001 to 15 psi. The miniature transducer (0.575 in. in diameter by 0.186 in. thick) has a time response on the order of 10 msec at the low absolute pressure (~ 0.001 psia) levels. A diaphragm-type VR transducer which reportedly measures pressures as low as 0.00003 psi is described by Heyser (52). Patterson (49) also discusses an instrument of this same type. References (51) and (53) describe a diaphragm-type VR transducer which incorporates a fast time-response pressure inlet port as well as acceleration compensation. The unit is designed to measure pressures from 0.001 to 0.1 psi with a time response on the order of 1 msec. The transducer is a double diaphragm device: one is the pressure sensor and the other acts as an accelerometer to cancel the acceleration effects. Two half-bridge variable reluctance configurations are provided, and if the two signals are properly summed the output caused by acceleration can be canceled.

2.2.2 Bourdon Tube Variable Reluctance Pressure Transducers

A VR transducing technique consisting of a twisted bourdon tube (12) is shown in Fig. 13. The instrument incorporates four inductance coils located on the magnetic core arrangement of Fig. 13a. The elastic element is a twisted bourdon tube (12) held rigidly at the open end and attached to a flat magnetic armature at the closed end. When pressure is introduced into the tube, it tends to untwist and therefore rotate the armature. This changes the air gaps in the magnetic core circuit such that the inductances of L_1 and L_2 (Fig. 13a) increase while L_3 and L_4 decrease or vice versa. With the four coils connected as shown in Fig. 13c, a four-active-arm full bridge is provided. Further variable reluctance theory may be found in (5) and (49).

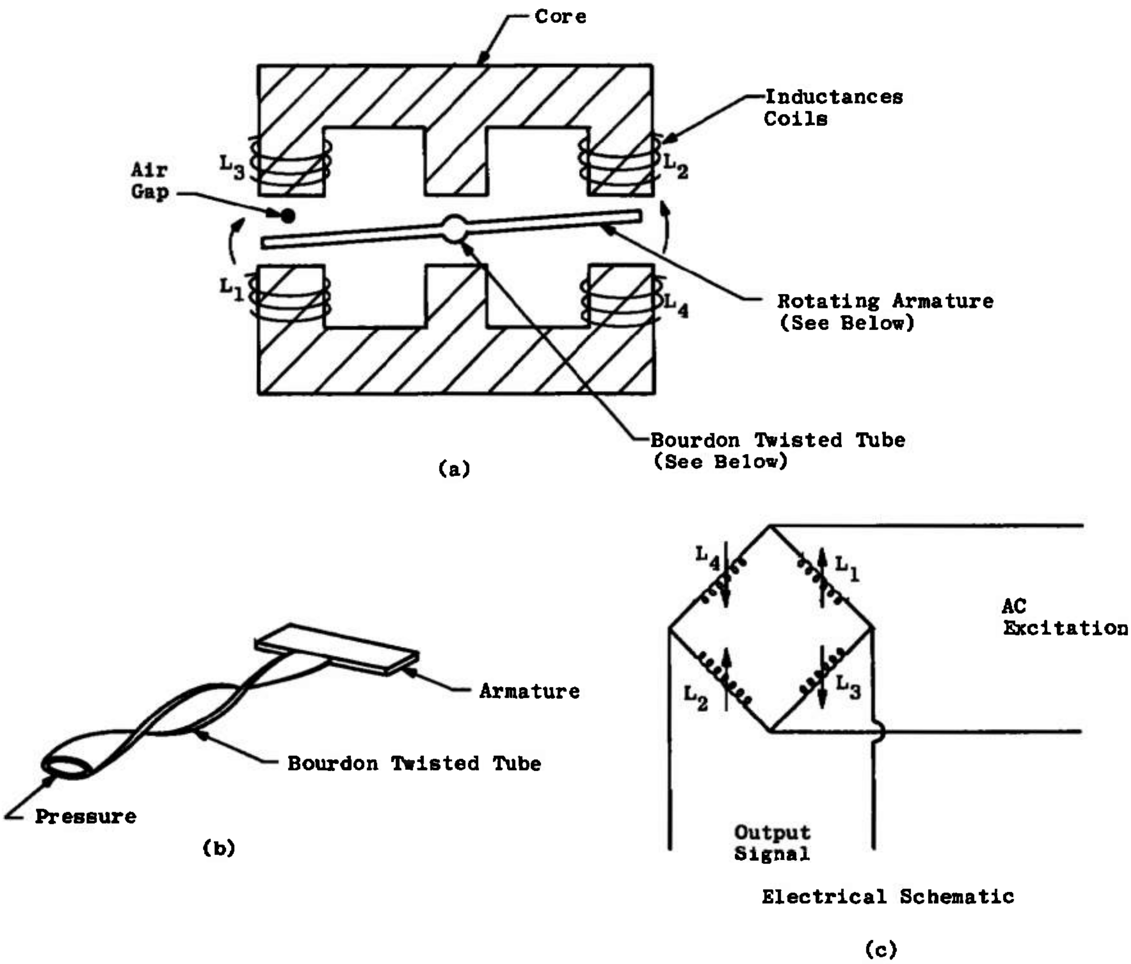


Fig. 13 Bourdon Tube Variable Reluctance Pressure Transducer

The twisted bourdon-tube-type transducer is generally not as effective for measuring dynamic pressure as is the diaphragm VR transducer (Section 2.2.1). The internal volume of the bourdon tube is often large enough to cause significant time lag (Section 3.1.2) especially at low absolute pressure levels. The

mass of the tube and the armature limits the resonant frequency (38) of the instrument and also renders it more sensitive to acceleration than the diaphragm type. The twisted tube transducer is seldom used for the measurement of very low pressures as the most applicable range is 5 to 10,000 psi. This transducer is not as susceptible to flow contaminations as is the diaphragm type because the pressure medium is confined to the bourdon tube interior, and hence the air gaps are protected. These transducers are normally larger than the diaphragm type and are not as applicable where space limitations exist.

2.2.3 Linear Variable Differential Transformer (LVDT) Transducers

The linear variable differential transformer (LVDT) (54 and 55) transducer consists of three coils wound on a form as shown in Fig. 14a. A magnetic core centered in the coils is free to be displaced by a pressure activated elastic element (12) such as a diaphragm, bellows, etc. The center coil is the primary winding of the transformer and requires AC excitation. The two outside coils form the secondaries of the transformer and are connected as shown in Fig. 14b. When the core is centered the induced voltages in these two secondary windings are equal and 180 deg out of phase, and therefore a zero is available. When the magnetic core is displaced by the action of the applied pressure, the voltage in one secondary increases and that in the other decreases. Hence, a voltage output proportional to the pressure input is provided.

The most notable advantage of the LVDT-type transducer is its high sensitivity as outputs up to 30 volts per psi are available (4). This permits pressures in the range of 0.001 psi to be measured. The dynamic response of the LVDT is limited by the relatively low resonant frequency created by the mass of the magnetic core and linkage; therefore, the instrument is more effectively used in measuring static pressures. The core mass also hampers the usefulness of the LVDT in areas of high acceleration. This type transducer is generally large (4) compared with many other types of transducers and often cannot be used because of this disadvantage.

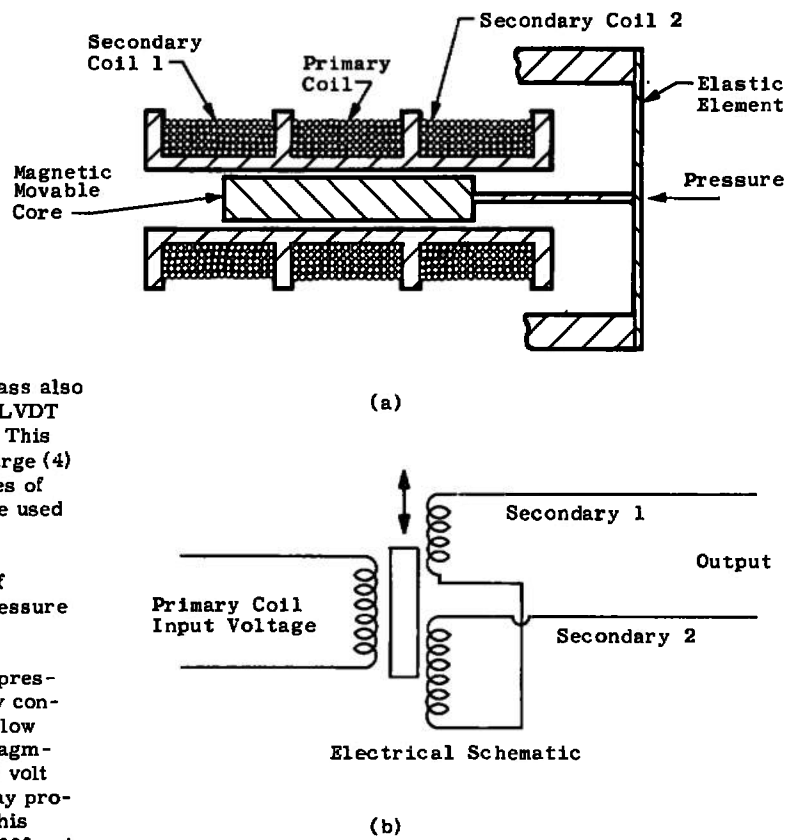


Fig. 14 Linear Variable Differential Transformer Transducer

2.2.4 General Performance of Variable Reluctance Pressure Transducers

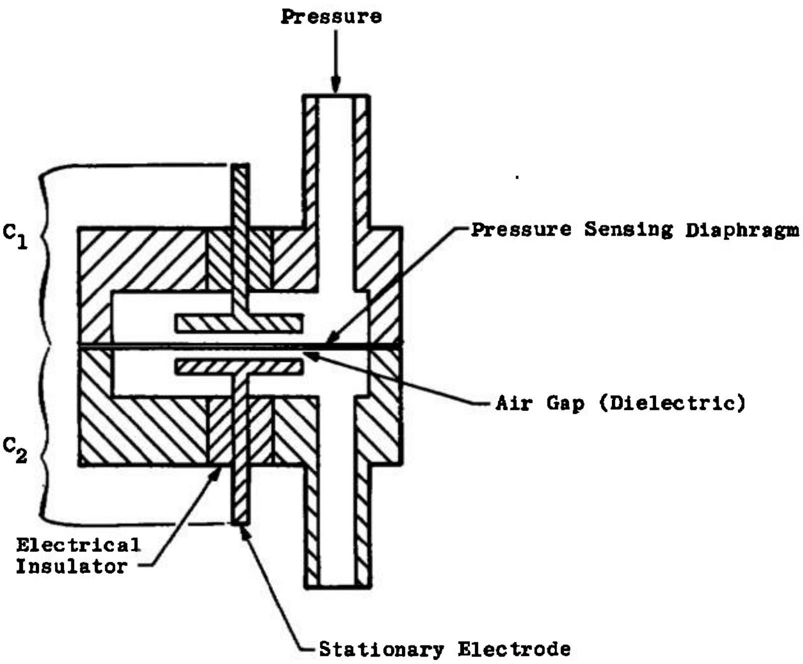
Variable-reluctance-type pressure transducers are generally considered to be high sensitivity, low pressure devices. The diaphragm-type provides outputs up to one volt per psi, whereas the LVDT may produce up to 30 volts per psi. This allows pressures down to 0.00003 psi to be measured. Although low pressure measurements provide the most frequent applications for the VR transducers, higher pressures up to 10,000 psi can also be measured, especially when the twisted bourdon tube technique is employed. The diaphragm-type normally provides faster time response than the other VR transducers discussed and is successfully used for many wind tunnel dynamic measurements. Variable reluctance transducers normally operate over a temperature range of approximately -65 to 250°F with a nominal temperature sensitivity of 0.02% per °F. More detailed specifications for transducers of this type may be found in the ISA "Transducer Compendium" (4).

2.3 Variable Capacitance Pressure Transducers

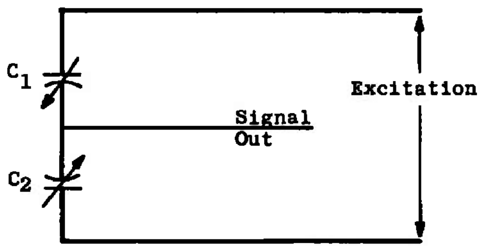
2.3.1 Three Electrode Variable Capacitance Pressure Transducers

A capacitance-type pressure pickup employing a metal diaphragm (12 and 30) or stretched membrane (12 and 30) separating two volumes is shown in Fig. 15. This is known as the three-electrode technique

and consists of stationary metal plates positioned on each side of the diaphragm such that a small air gap (≈ 0.001 in.) dielectric is provided between the pressure sensing diaphragm and the stationary electrodes. When a pressure is applied, the diaphragm will deflect toward one of the stationary electrodes and away from the other. This movement of the diaphragm changes the capacitance between it and the plates; capacitance increases with one of the plates while decreasing with the other. The electrodes are normally connected as shown in Fig. 15b to form a two-active-element device which may be employed in an AC bridge or other signal conditioning circuitry as discussed in Section 3.2.4. A more detailed treatment of the variable capacitance theory is given by Neubert (5).



(a)



Electrical Schematic

(b)

Fig. 15 Three-Electrode Variable Capacitance Pressure Transducer

An outstanding feature of this type of transducer is its ability to measure extremely low pressures. With the proper signal conditioning, pressures as low as 0.0000002 (2×10^{-7}) psi (56) may be measured, and the instrument is often used as a pressure standard for the calibration of other pressure sensors, especially in this low pressure differential regime. This three-electrode transducer is commonly used for static pressure measurements but with the proper design of the internal volume and pressure inlet tube (Section 3.1), the transducer response is adequate for many dynamic applications. This transducer provides the same advantages offered by other types of transducers which employ a diaphragm elastic element, that is, high resonant frequency, low sensitivity to acceleration (because of low seismic mass), and high acceleration survival capability.

Because of the small air gap (≈ 0.001 in.) between the diaphragm and the stationary electrodes, this instrument is susceptible to particle contamination. Any particles which exist in the pressure media may be lodged in this small air gap and hence restrict the movement of the elastic element or possibly change the dielectric characteristics of the variable capacitors. Particle or dust filters may be employed in the pressure inlet tube to minimize this problem; however, the response characteristics of such filters must be compatible with the application. The relationship between (applied) pressure and capacitance change for this transducer is nonlinear (5), especially for the larger diaphragm deflections. The nonlinearity is compensated out to some degree by use of this three-electrode, push-pull arrangement since the diaphragm is moving toward one electrode and away from the other. A nominal non-linearity error for the three-electrode instrument is 1.5 percent of F.S., but this error may be reduced to ±0.025 percent with proper signal conditioning (56).

MacDonald and Cole (57) describe a three-electrode capacitance-type transducer designed for wind tunnel pressure measurements. This miniature (0.125- by 0.25- by 0.375-in.) transducer is designed to measure pressures up to 4 psi and has a sensitivity of one volt per psi which permits pressures down to approximately 0.05 psi to be detected. Another transducer of basically the same type is presented by Dimeff (58). This instrument was designed in full-scale ranges from 0.01 to 0.4 psi for measurements in a low density wind tunnel.

2.3.2 Two-Electrode Variable Capacitance Pressure Transducers

A variable capacitance pressure transducer employing only two electrodes is shown in Fig. 16. This type is similar to the three-electrode configuration in operating principle (5), but it has a stationary electrode positioned on only one side of the diaphragm, and therefore only one active element (capacitance)

is provided. The instrument is normally arranged so that an applied pressure causes the diaphragm to deflect toward the stationary electrode, decreasing the air gap (dielectric) and hence increasing the capacitance between the diaphragm and the stator. An electrical schematic of the one active element is shown in Fig. 16, and it may be operated into a variety of signal conditioning circuits as discussed in Section 3.2.4.

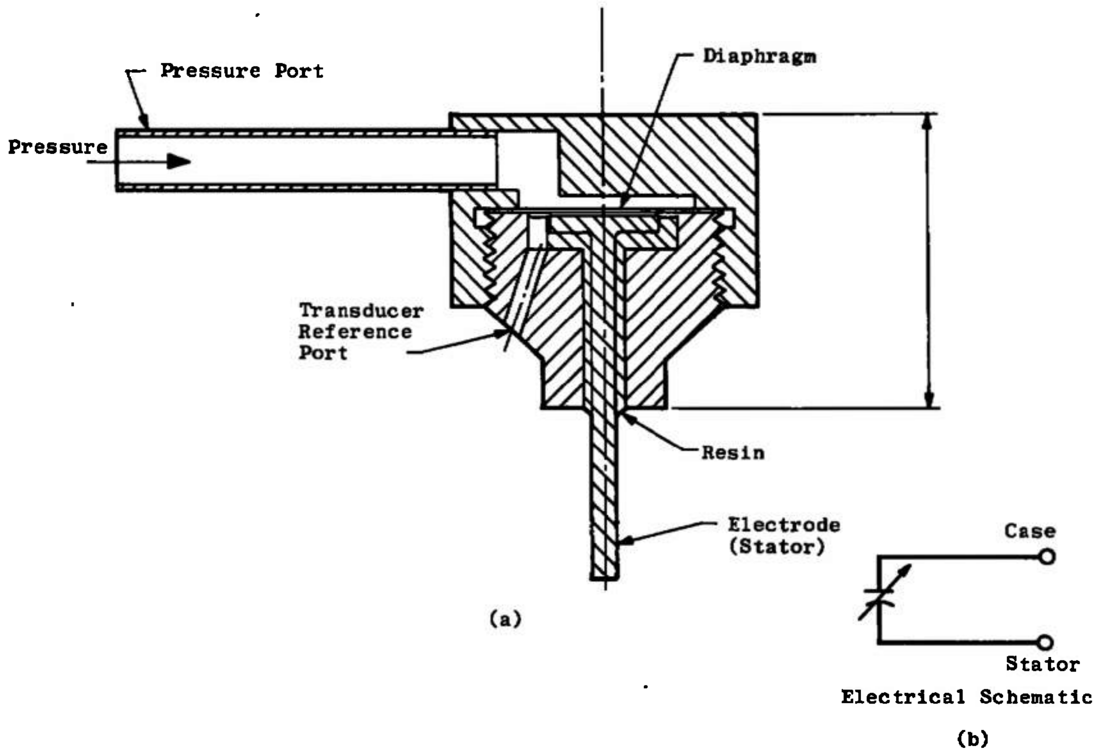


Fig. 16 Two-Electrode Variable Capacitance Pressure Transducer

This technique is probably more widely used than the three-electrode configuration mainly because it is simpler to build. Obviously, the small air gaps are difficult to obtain, and since the two-electrode configuration incorporates only one such gap, construction time is reduced. The two-electrode technique offers another advantage in that it is not susceptible to particle contamination. With the pressure applied as shown in Fig. 16, it is evident that the small air gap (dielectric) is not exposed to the pressure media; therefore, the main cause of the contamination problems is eliminated. Since the two-electrode transducer employs only one stationary electrode, the pressure inlet port may be built with few restrictions and even in a flush diaphragm configuration. This means it would be more applicable than the three-electrode pickup (Fig. 15) for many dynamic measurement requirements. A significant problem associated with the two-electrode transducer is its non-linearity (5). This single element pickup does not possess the inherent non-linearity compensation of the three-electrode (two-active-element) instrument and non-linearities up to 10 percent are not uncommon. This non-linearity may be reduced, however, by use of the appropriate signal conditioning equipment. Since the two-electrode configuration employs only one active element, it provides approximately half the sensitivity (provided other parameters are equal) of the three-electrode device and therefore, is less effective for low pressure measurements.

A two-electrode variable capacitance transducer designed to measure shock tunnel pressures up to 2 psi is considered by Dimeff (58). This sensor is only 0.2 in. in diameter and is fabricated in a flush diaphragm configuration for fast time-response characteristics. A transducer of this type designed by Coon (59) and discussed by McDevitt, et al. (60), is employed in a FM telemetry circuit (Section 3.2.4) to telemeter pressure data from a free-flight model in wind tunnel tests. This variable capacitance device is 0.25 in. in diameter by approximately 0.25 in. long and has a full-scale pressure range of 0.10 psi. The time duration of the free-flight pressure test for which this transducer is employed is on the order of 100 msec. A transducer similar to this and also used for free-flight model pressure measurements is described by Harrison (61). This particular unit is 0.342 in. in diameter by 0.189 in. long and is capable of measuring pressures down to ≈ 0.002 psi.

Figure 17 shows a two-electrode variable capacitance transducer (62) designed for free-flight pressure measurements in a gun range facility at the AEDC. This 0- to 10-psi transducer incorporates a unique reference pressure system which provides a constant reference pressure during the test flight time (≈ 100 msec). This condition is accomplished with a reference tank, which encloses the transducer,

and a lag line (10-in. length of 0.010-in. -ID tubing). The response characteristics of this reference pressure system are such that the reference pressure at the back side of the diaphragm does not appreciably change during the flight time. This transducer was designed to survive acceleration levels up to 250,000 g's which may be imposed during the launching process. The reference pressure tank which is built around the transducer provides a very important function for this capability as it isolates the transducer from hydrostatic pressure or other spurious forces which may be set up in the telemetry package (62) during the launch.

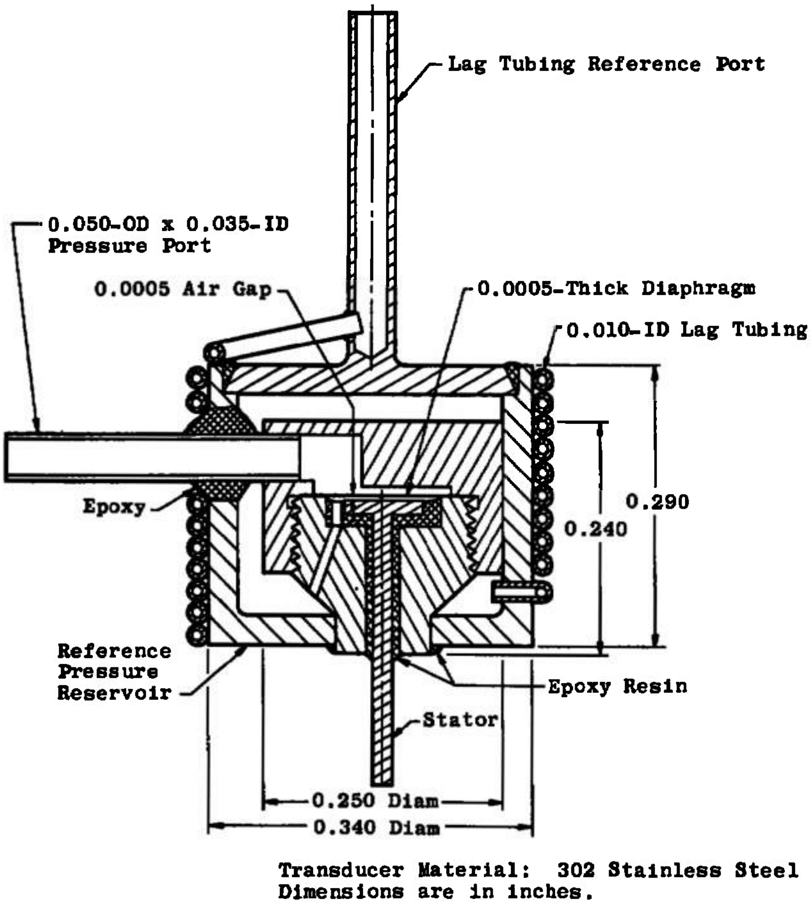


Fig. 17 Capacitance Transducer with Built-In Reference Pressure Lag System

Another capacitance transducer developed for employment in a telemetry package for the measurement of wind tunnel free-flight model pressures is reported by Choate (62, 63, and 64). This transducer is larger (0.750 in. in diameter by 0.400 in. thick) than the telemetry transducers discussed above, but it is used to measure pressures down to 0.0005 psi. The instrument is also equipped with a reference pressure lag system similar to that discussed previously for the transducer in Fig. 17.

Posel (65 and 66) discusses a two-electrode variable capacitance transducer incorporating a composite dielectric. This arrangement differs from the conventional two-electrode device in that the dielectric (between diaphragm and stationary electrode) is made up of an air gap plus a thin layer of mica instead of just an air gap. This configuration is reported to improve the linearity characteristics of the two-electrode device; however, doubts as to the effectiveness of this technique are expressed by Neubert (5).

2.3.3 Variable Capacitance Pressure-Bar Gages

Short-duration pressure pulses or step-function pressures with steep fronts may be measured by use of the variable capacitance pressure-bar gage shown schematically in Fig. 18. This configuration consists of a thin (~0.003 in.) dielectric located between two electrodes to form a capacitor on a rod or bar as shown. The transducer operates on the principle (67 and 68) that when a pressure is applied to the front (top) of the bar configuration, a traveling wave passes through the dielectric (capacitor) and continues along the bar until it is reflected at the end. During the passage of this wave through the dielectric, the capacitance between the electrodes is changed in proportion to the pressure. If the duration of the pressure pulse is less than the time required for the wave to pass down the length of the bar and return to the dielectric (capacitor), a meaningful record of the pressure input may be obtained.

However, when the reflected wave returns to the sensor (dielectric), the output will be a result of both the pressure input and the reflected wave, and hence the information obtained is complex and normally unusable. The fabrication of these transducers is generally difficult since the bonding faces between the dielectric, electrodes, and bar must be such that the traveling wave is not reflected at any of these locations. This condition may be established by selecting materials (for the dielectric, electrodes, and bar) whose acoustic impedances are equal. This detail of construction is fully treated by Baganoff (67) and Davies (68).

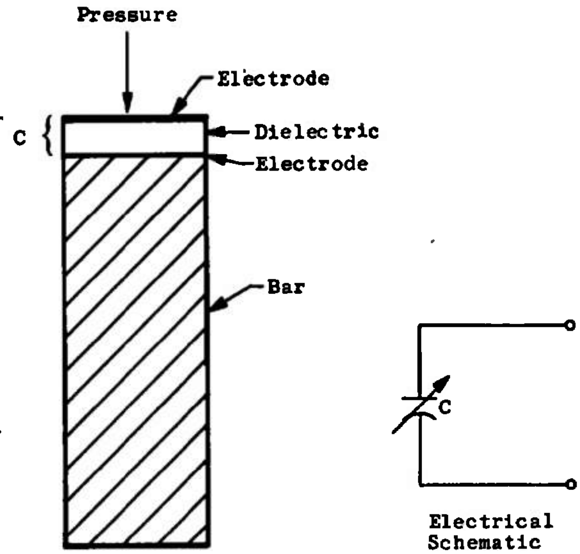


Fig. 18 Variable Capacitance Bar Gage

This transducer is used mainly for pressure measurements in shock tube facilities. Baganoff (67) describes a pressure bar gage which has a rise time of approximately 0.1 μsec and can measure pressure pulses up to 5 μsec in duration. This instrument is relatively large in size (1.375 in. in diameter) and was designed to measure pressures in the range of 0.2 to 1 psi. Baganoff also discusses (69) a modification (primarily size) of this transducer which increased the dwell time from 5 to 23 μsec. Another improvement of this bar gage (70) incorporates an electrical insulating sheet on the front of the top electrode so as to isolate the sensor from the flow and hence protect the device from the effects of flow ionization. The reader is also referred to Section 2.4.3 for a discussion of a similar bar gage using a piezoelectric element instead of the capacitance sensor.

2.3.4 Summary of Performance of Variable Capacitance Pressure Transducers

Probably the most outstanding feature of the variable capacitance transducing techniques is its capability to measure low pressures, as levels down to 2 x 10^{-7} psi (56) may be detected when the appropriate signal conditioning equipment is employed. The majority of variable capacitance transducers utilize diaphragm or stretched membrane elastic elements, and, therefore, they are applicable in many areas where accelerations exist. The types of capacitance devices discussed here permit the measurement of pressures in a time regime from static for the diaphragm type to a 0.1-μsec rise time for the pressure-bar. A frequent measurement application of the diaphragm-type variable capacitance transducer is in telemetry systems. The capacitive characteristic of the instrument makes it especially convenient to employ in the oscillator circuit of common telemetry transmitters.

Although this type instrument is generally considered a low pressure device, pressure ranges up to 10,000 psi may be provided. Variable capacitance transducers which operate over a temperature range of -55 to +225°F with a temperature sensitivity as low as 0.01% per °F are available. More complete specifications on various variable capacitance pressure transducers are given in (4).

2.4 Piezoelectric Pressure Transducers

Cady (71) defines piezoelectricity as an electrical polarization produced by mechanical strain in crystals belonging to certain classes, the polarization being proportional to the strain and changing sign with it. When a piezoelectric element is stressed mechanically, its dimensions change and it generates an electric charge. If the element electrodes are not short circuited, a voltage associated with the charge appears. This type sensor, unlike those previously discussed, is self-generating, that is, it does not require external electrical power as do the variable resistance, variable reluctance, etc. The relationship between the applied stresses and the resulting electrical output depends on the physical and piezoelectric properties of the elements and this theory is treated extensively in (71), (72), and (73). The Kistler Instrument Corporation (74) presents a unique and effective explanation of this basic piezoelectric phenomenon through the following analogy.

Among familiar hydraulic circuits, there exists a simple analogy (Fig. 19) to a piezoelectric system. An elastic, saturated sponge joined by a tube to a fluid container closely resembles an elastic crystal saturated with electrons and connected to a container for electrons, a capacitor. When an externally applied force deforms the elastic structure of either system, the ejected quantity of liquid or electrons fills respective containers to some potential (H or V) directly proportional to the quantity and inversely proportional to the container size. Releasing the force reverses the process. A dump valve in the bottom of the fluid container functions the same as a shorting switch across the capacitor to quickly empty the container of any accumulation. A leak in the fluid container acts like a leakage resistance around the capacitor to also empty the container, but at a slower rate.

Analogous physical parameters discussed above determine the response to transient (Fig. 20) or oscillatory input forces. The level (amplitude) of the hydraulic or electrical potential serves as an

information bearing signal for instrumentation or control systems. The signal resulting from a steady force input remains indefinitely when there is no leak (infinite resistance to flow). With a finite leak, the signal exponentially decays to zero because the leakage flow decreases as the potential drops. If the discharge continued at its initial rate following a step function input, the container would empty in one time constant equal to the product of the resistance times the capacitance. When a transient event occurs within one percent of this storage time constant, the distortion attributable to leakage is also less than one percent. Thus, over the event-time interval, the system effectively exhibits static response. Under ideal conditions, quartz transducers and electrostatic charge amplifiers (Section 3.2.3) store signals for days or even weeks. The ability of a system to follow low-frequency, repetitive events relates directly to its storage capabilities.

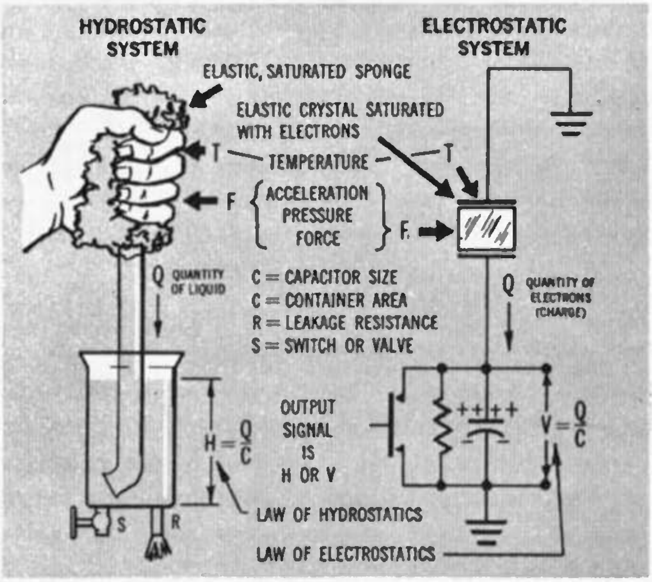
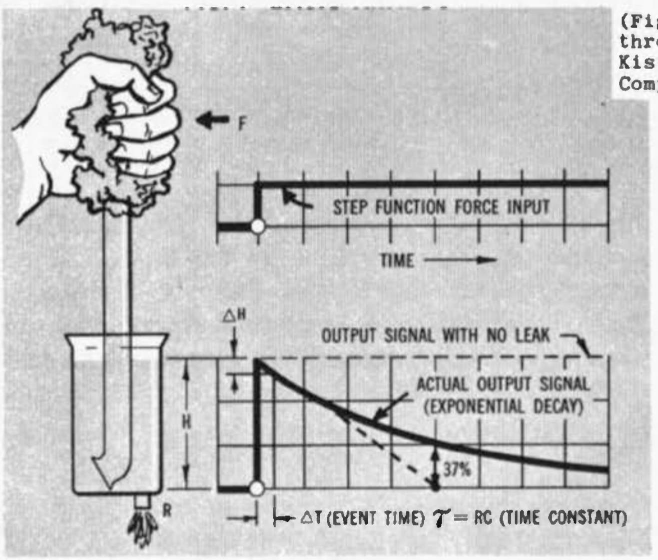


Fig. 19 Basic Analogy of a Piezoelectric System



(Figures Reproduced through Courtesy of Kistler Instrument Company)

Fig. 20 Transient Response

A variety of piezoelectric materials are used, with quartz, barium titanate, and lead zirconate titanate being the most popular. Neubert (5) tabulates the physical and piezoelectric properties for these materials and many others sometimes used. Quartz crystals are selected from those found in their natural state, and the elements are made from slabs cut from the crystal with careful attention to the existing crystallographic (71) axes. The ceramic elements (barium titanate, lead zirconate titanate, etc.) are formed from finely powdered materials that are pressed into the desired shape and then sintered by firing at high temperatures. The piezoelectric effect is created as they are polarized by exposure to an electric field during the cooling after the firing process.

Piezoelectric elements will reach a Curie point when heated. At this Curie point temperature the crystalline structure changes, polarization is lost, and hence the piezoelectric effect is destroyed. Quartz elements have a Curie point of approximately 1000°F, whereas this temperature for some of the ceramic elements is as low as 250°F. The output of a piezoelectric element may also be affected by the pyroelectric effect (71) which causes changes in output proportional to the change in temperature experienced by the crystal. The pyroelectric effect for quartz is negligible but is very pronounced for most of the ceramics. From these characteristics, it is evident that the quartz element is more applicable in areas of temperature change and especially in areas of high operating temperatures. Although the quartz element has a weaker pyroelectric effect, most transducers incorporating quartz crystal possess a significant zero drift with temperature change. A large portion of this drift is probably caused by the element mounting configuration which includes coefficient of temperature expansion mismatches. For many measurement applications, techniques for isolating or protecting the transducer from these hostile temperature environments have been devised and are discussed in Section 3. 1. 1.

The charge sensitivity of ceramic elements is generally 10 to 100 times greater than that for quartz elements, and hence the ceramic elements are often more effective in the measurement of low pressures. Because of its low dielectric constant and thus capacitance, quartz provides a voltage sensitivity approximately twice that of most ceramics. This advantage is normally not realized in measurements applications because of the large amount of capacitance effectively added to the element by the required cable between the transducers and the signal conditioning (Section 3. 2. 3). Recent advances in the transistor and microelectronics field have led to the design of miniature voltage amplifiers (or followers) which may be packaged directly behind the piezoelectric element in the transducer (Section 3. 2. 3). This configuration may be used to take advantage of the high voltage sensitivity of quartz since very little capacitance is added between the element and the signal conditioning (internal amplifier). Refinements and improvements of this technique would certainly make the quartz element more effective for low pressure measurements. The mechanical properties of quartz allow it to be used at much higher pressures than is possible for the ceramic element. Transducers employing quartz crystals are available in pressure ranges up to 100, 000 psi, whereas the ceramic-type transducers are generally limited to 5000 psi.

Although normally restricted to dynamic measurements, piezoelectric-type pressure transducers, when used with the appropriate signal conditioning equipment, are capable of near static response (Section 3. 2. 3). Semi-static calibrations are possible under favorable environmental conditions, and short-term static and very low frequency measurements are sometimes obtained.

Since the internal resistance of the piezoelectric element is high (10^{10} to 10^{14} ohms) and the capacitance is low (5 to 500 pF), a slight leakage resistance path across the element electrodes or across the electrical connector pins can cause erratic operation and limit the low frequency response of the sensor. Hence, care must be taken to protect the piezoelectric element and all connectors from moisture or other contaminants that might create conduction paths.

2.4.1 Compressive Element Piezoelectric Pressure Transducers

A convenient and effective method of employing piezoelectric sensors in pressure transducers is shown in Fig. 21. The disk shape piezoelectric element is placed between the diaphragm and the transducer body (insulation). The diaphragm-shell assembly is threaded tightly onto the body to pre-load the sensing configuration so as to obtain high natural frequencies. With the pressure applied as shown, the piezoelectric element is compressed and a charge associated with the thickness mode characteristics of the element is generated across the electrodes on the faces of the disk (5 and 71). The diaphragm has a very low stiffness compared to the piezoelectric element, and its function is to provide the mechanical pre-load as well as a pressure seal to protect the element from the pressure medium. This flush mounted design coupled with its high natural frequency (100 kHz or greater) allows the transducer to respond to rapidly varying pressures. Transducers of this type are used at the AEDC to measure pressures ranging from 0. 1 to 10, 000 psi in a shock tunnel with a useful run time of approximately 1 msec. The lower pressure measurements (0. 1 to 300 psi) are accomplished by use of lead zirconate titantate elements while quartz is employed for the higher pressures (100 to 10, 000 psi). Clemente and others (75) describe a transducer of this type which utilizes a barium titanate-lead zirconate element to measure pressures ranging from 3 psi to 100 psi in a shock driven facility. The transducer is extremely small, being 0. 5 in. long by only 0. 1 in. in diameter and has a rise time of approximately 5 μsec. Goodchild, et al. (76) also discuss piezoelectric transducers of this type which have a resonant frequency on the order of 50 kHz with sensitivities around 50 picocoulombs/psi.

The charge sensitivity of a transducer of this type may be increased by using a "stack" of piezoelectric elements (5) as shown in Fig. 22 instead of the single element device of Fig. 21. Each of the elements in the stack is subjected to the same compressive force due to the applied pressure. When the elements are electrically connected in parallel (Fig. 22b), the charge outputs of the individual elements are added, and hence the output level is directly proportional to the number of elements in the stack. This type is obviously more expensive and more difficult to build than the single element transducer, but it may be more effectively used in the measurement of low pressures.

Another compressive element transducer configuration is shown in Fig. 23. This arrangement is similar to that of Fig. 21 with the exception that the sensor pre-load is accomplished by a thin wall tube placed in tension over the element or stack (Fig. 23). This type transducer (5) is more difficult to build

than the diaphragm pre-load type (Fig. 21); however, higher resonant frequencies are generally obtained. Commercial transducers of this type (4 and 74) with resonant frequencies on the order of 500 kHz are advertised.

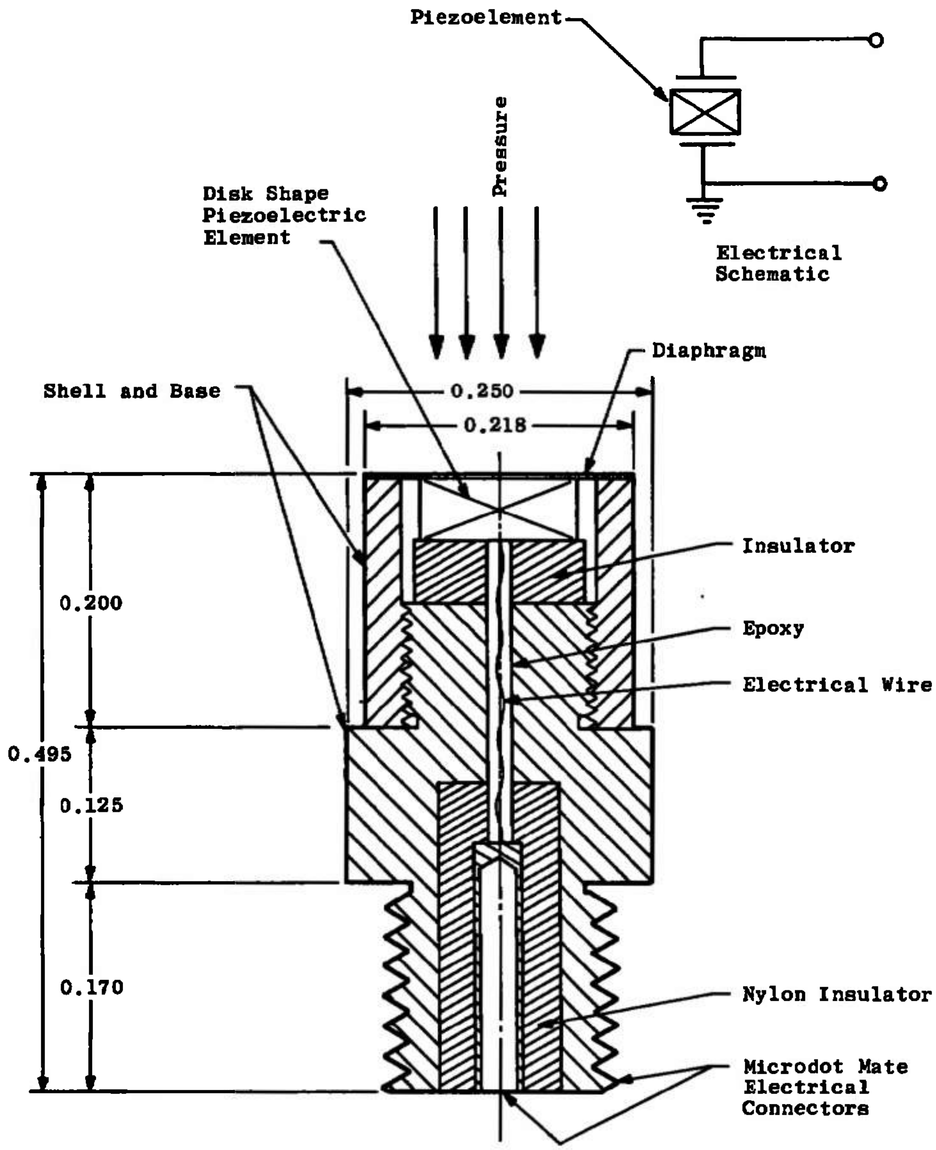


Fig. 21 Compressive Element Piezoelectric Pressure Transducer

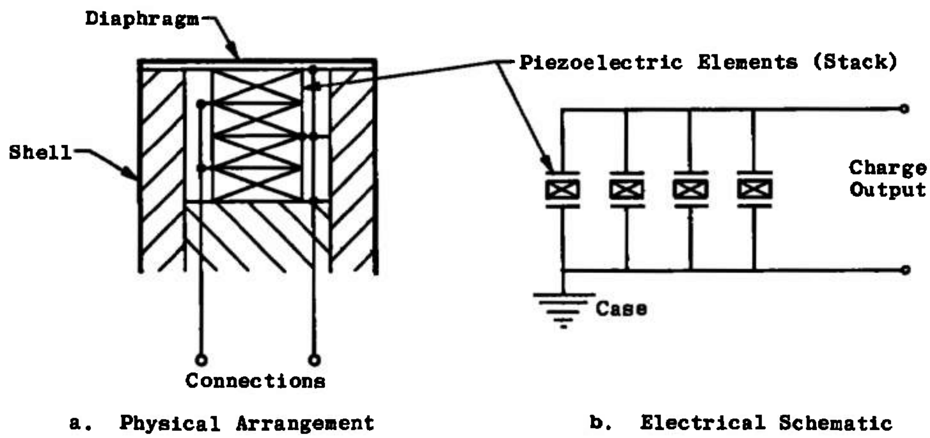


Fig. 22 Piezoelectric "Stack" Transducer

The compressive element transducing technique shown in Fig. 24, unlike the devices (Figs. 21 and 23), discussed above, does not incorporate a pre-load of the piezoelectric element. Since no diaphragm is used, the element is protected from the flow environment by an epoxy or other insulating material surrounding the crystal. This type construction can result in low resonant frequencies, and errors caused by side loading of the element may result as the protective material is compressed around the piezoelectric elements during the pressure application. This instrument is, however, simple and inexpensive to build and may be used in many applications, especially those in which only "time of arrival of the pressure step" information is desired. Levine (77) discusses a sensor of this type used to measure pressures ranging from 0.5 to 1000 psi in a shock tube wind tunnel. The device employs a barium titanate piezoelectric element which is encapsulated in a neoprene potting for protection. A compressive element transducer utilizing a nylon disk cemented on top of the element (lead-metaniobate) instead of the potting technique mentioned above is described by Granath and Coulter (78). The instrument is built in two sizes (0.5- and 0.25-in. diameters) and is used to measure pressures ranging from 0.2 to 30 psi in shock tube tests.

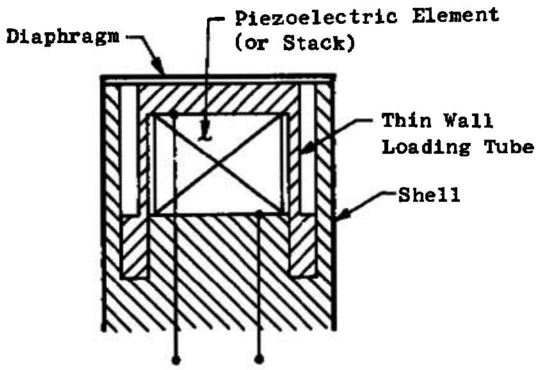


Fig. 23 Tube Loaded Piezoelectric Pressure Transducer

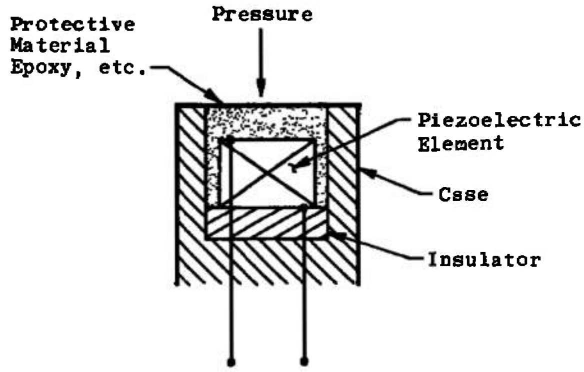
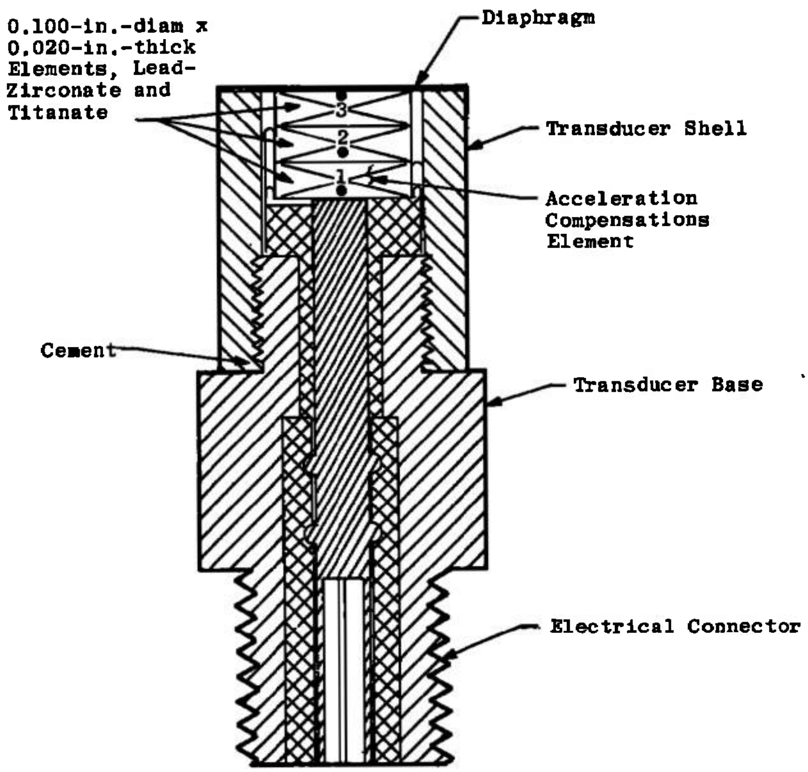


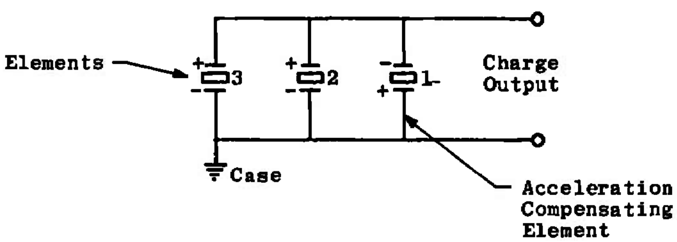
Fig. 24 Compressive Element (No Pre-Load) Transducer

The acceleration effects of a compressive-element-type transducer can be minimized by the proper mechanical design, that is, the seismic mass (diaphragm and piezoelectric element) should be low. However, in some instances, this is not adequate and acceleration compensation is desirable. Such a technique is shown in Fig. 25. The transducer is used at the AEDC for measurement of pressures from 0.1 to 100 psi in a shock tunnel. It consists of three lead zirconate titanate elements employed in a "stack" which is pre-loaded by the diaphragm (Fig. 21). The three elements are electrically connected in parallel with the polarity of the bottom element (No. 1) reversed with respect to the top two elements (Nos. 2 and 3) as shown in Fig. 25b. Each of the elements witnesses the same compressive stress when a pressure is applied, but since the polarity of the bottom element (No. 1) is reversed, it cancels the charge output caused by the pressure of one of the other elements, and hence a resultant charge output (attributable to pressure) of only one element is realized. Since the acceleration compensating element is located at the bottom of the "stack," the seismic masses are distributed so that the output of the element is approximately equal to the outputs of the other two elements (Nos. 2 and 3) for a given acceleration level. With the polarity of the bottom element reversed (Fig. 25) from that of the other two, it is evident that the charge outputs of the three elements (attributable to acceleration) will cancel. The compensated transducer of Fig. 25 has an acceleration sensitivity of 0.001 psi or less per g compared to a value of 0.01 psi per g for a transducer of similar construction (Fig. 21) but without acceleration compensation. If an acceleration-compensated transducer of higher pressure sensitivity is desired, more than three elements may be used and a metal disk of the appropriate weight can be located directly on top of the compensating element such that the required seismic mass ratio for compensation is obtained. Commercial transducers (74) of this type with a quoted acceleration sensitivity of 0.001 psi per g are available. Obviously, this acceleration-compensated piezoelectric pressure transducer, with its flush-mounted configuration, is extremely useful in shock tunnel facilities when low pressures in the presence of vibrations are to be measured.

A compressive element transducer with a somewhat different acceleration compensation technique is discussed by MacArthur (79) and is shown in Fig. 26. The compensating disk is mounted on a separate support from that of the pressure sensing element and is not linked to the pressure sensing diaphragm. With the outputs from the pressure sensing and compensating element added, compensation is accomplished and an acceleration sensitivity of 0.005 psi per g is provided. The transducer is extremely small (0.125 in. in diameter) and contains within its shell a field effect transistor (FET) amplifier (Section 3.2.3). This transducer is designed to measure pressures from 0.1 to 100 psi in a shock tunnel. Another transducer incorporating this same acceleration compensation technique is described by Goodchild, et al. (76)

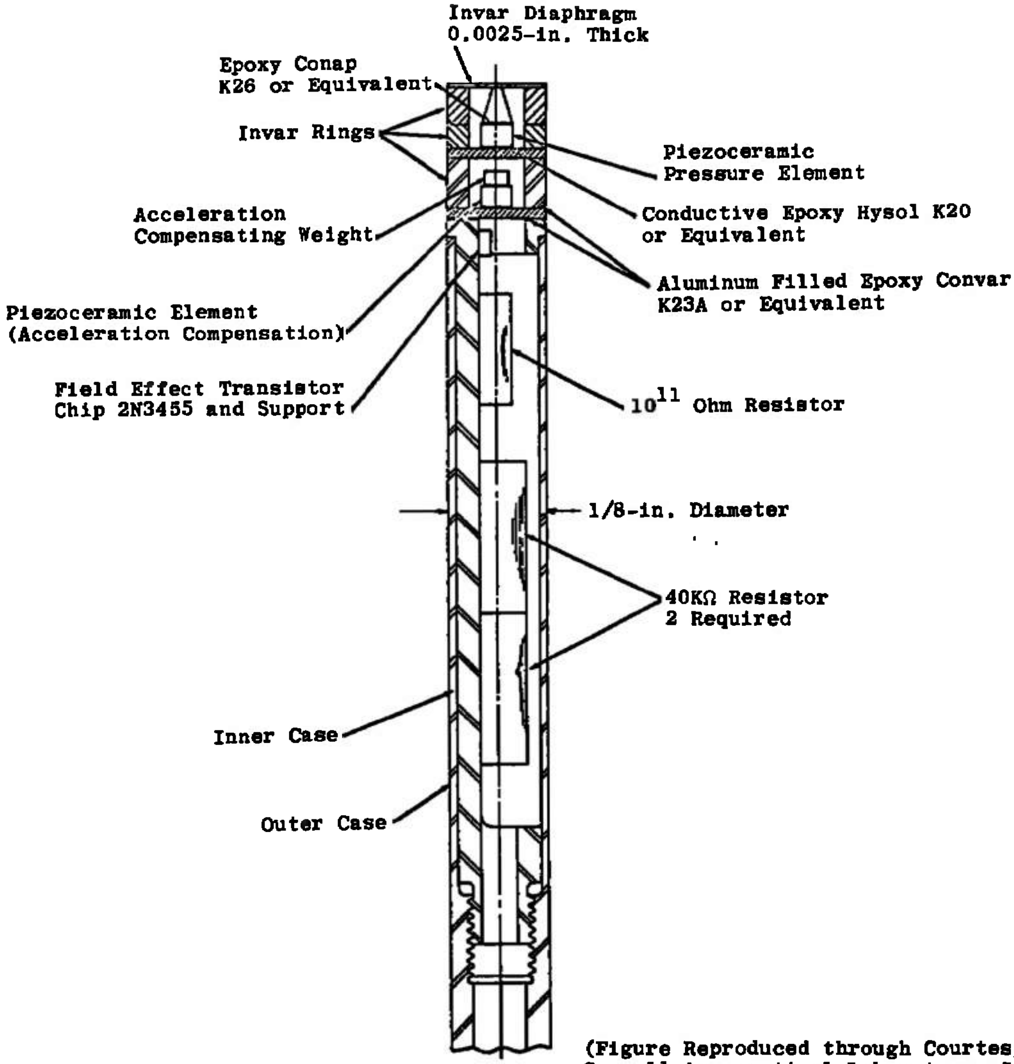


a. Physical Arrangement



b. Electrical Schematic

Fig. 25 Acceleration-Compensated Compressive Element Transducer



(Figure Reproduced through Courtesy of Cornell Aeronautical Laboratory, Inc.)

Fig. 26 Cornell Compressive Element, Acceleration-Compensated Pressure Transducer

2.4.2 Beam-Type Piezoelectric Pressure Transducers

If two rectangular length expander piezoelectric elements are cemented together as shown in Fig. 27, a so-called "bimorph" (7) is formed. This arrangement allows the crystals to be employed as a simple or cantilever beam so as to sense the bending stress caused by a force applied like that in Fig. 27. This piezoelectric sensor permits a much larger deflection than the compressive element for a given force; therefore, increased sensitivity is provided. However, this higher output is obtained at the expense of mechanical stiffness, and hence the "bimorph" device normally has a lower resonant frequency than the compressive element type (Fig. 21).

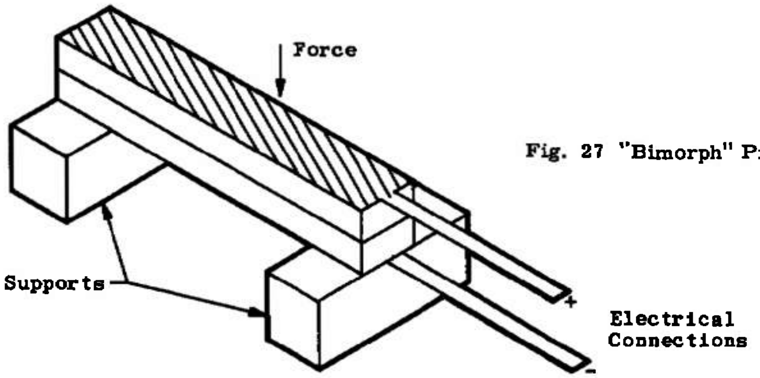
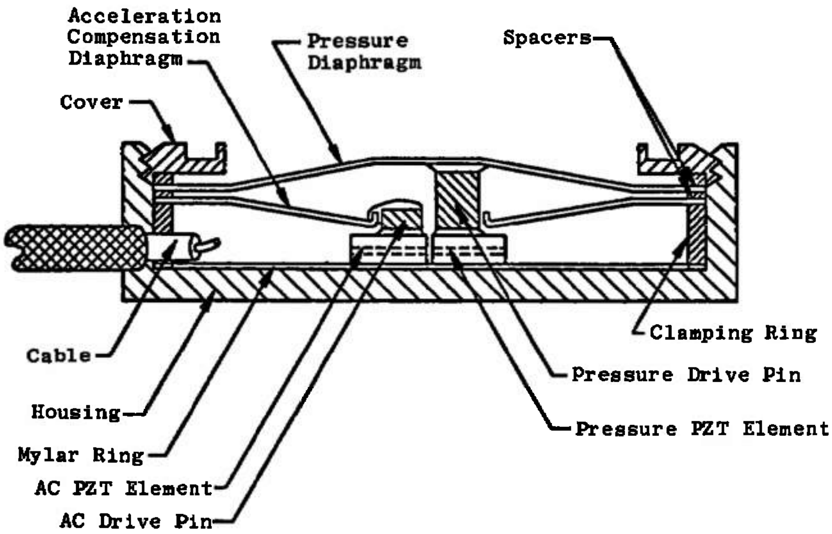


Fig. 27 "Bimorph" Piezoelectric Element

A beam transducer designed for the measurement of low pressures in a shock tunnel has been developed at Cornell Aeronautical Laboratory and is described by Martin, et al. (80 and 81) and is shown in Fig. 28. The "bimorph" element is separated from the pressure sensing diaphragm by an insulating drive pin to provide a temperature barrier, thereby preventing spurious signals from crystal heating. This instrument is also equipped with a "bimorph" element activated by an acceleration-compensating diaphragm which is not subjected to the pressure to be measured. With the outputs from these two "bimorphs" added, acceleration compensation is accomplished. This transducer is 0.5 in. in diameter by 0.125 in. thick and is designed to measure pressures in the range of 0.0005 to 0.5 psi. Two other transducers of basically this same construction, which were also developed at Cornell, are discussed by MacArthur (79). These transducers are much smaller (0.125-in. and 0.25-in. diameters) and are also equipped with a "built-in" FET amplifier (Section 3.2.3). This outstanding feature allows both the pressure sensor and the signal conditioning to be located at the same point, therefore eliminating the problems normally associated with the cabling between the transducer and the signal conditioning. Both of these transducers incorporate internal acceleration compensation with the 0.125-in. diameter model having an acceleration sensitivity of 0.005 psi per g and the 0.25-in. device 0.0004 psi per g. The 0.125-in. diameter transducer is designed to measure pressures ranging from 0.1 to 100 psi, and the 0.250-in. diameter model operates from 0.001 to 3.0 psi. Another piezoelectric beam-type transducer is presented by Lederman, et al. (82). This instrument also incorporates an acceleration compensation beam which provides the transducer with an acceleration sensitivity of 5×10^{-4} psi per g. Pressures ranging from 0.001 to 0.5 psi are reportedly measured.



(Figure Reproduced through Courtesy of Cornell Aeronautical Laboratory)

Fig. 28 Cornell Beam-Type Piezoelectric Pressure Transducer

2.4.3 Piezoelectric Bar Gage

A schematic of the basic piezoelectric bar gage (7 and 73) is given in Fig. 29. It consists of a piezoelectric element attached at one end of an elastic rod. When a pressure step is applied as shown (Fig. 29), the piezoelectric element is axially strained and hence a charge output is provided. This axial strain is constant until the pressure wave is reflected at the element-rod junction or the end of the rod and returns to the element. When the reflected wave returns to the crystal, the output is then a result of this reflected wave as well as the pressure step, and hence the information obtained is meaningless. This characteristic limits the length of time (dwell time) over which the transducer can be successfully used. If the elastic mounting bar is fabricated from a material with the same acoustic impedance as that for the piezoelectric element, theoretically, the pressure pulse will pass from the crystal to the bar without reflections. Therefore, the usable time (dwell time) of operation of the unit will not be terminated until the wave is reflected at the free end of the bar and returns to the element. This transducer is often used to investigate the initial rise of shock tube pressure steps or other short-duration pressure fluctuations.

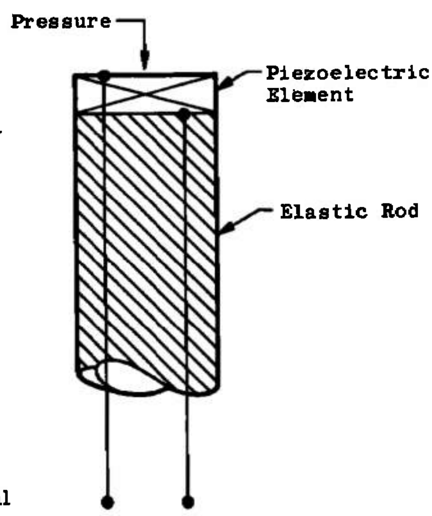


Fig. 29 Piezoelectric Bar Gage Schematic

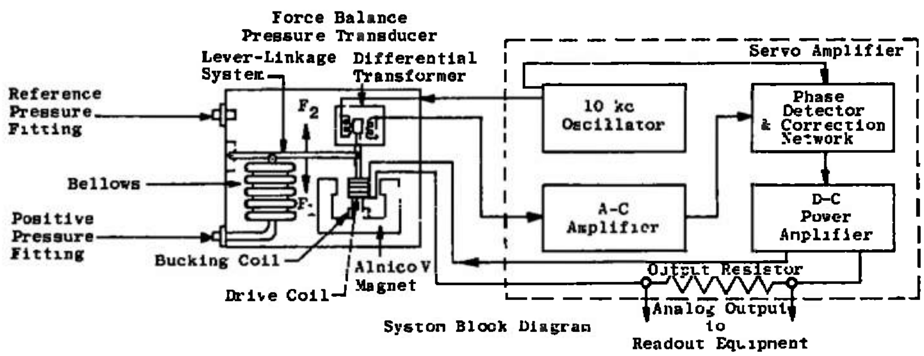
Edwards (83) describes a bar gage which has a rise time of approximately 15 μsec and a dwell time of 300 μsec. The instrument employs a quartz element mounted on an aluminum alloy rod. This transducer was later modified (84) to increase its "dwell time" by tapering the elastic rod and by placing it in a wax sheath, thereby attenuating the stress wave as it traverses the rod. A gage of this same type which utilizes a lead elastic rod and a barium titanate crystal is presented by Davies and Lippiatt (85). Another piezoelectric bar gage with a rise time on the order of 1 μsec is discussed in (86). Pressure measurements ranging from 0.05 to 300 psi are accomplished by use of these instruments.

2.4.4 Summary of Performance Characteristics of Piezoelectric Transducers

Although piezoelectric transducers may be used for near-static pressure measurements, they are more frequently employed for transient measurements. The inherent high resonant frequency coupled with the flush-mounted configuration generally used makes these transducers especially applicable in observing fast-rise pressure steps associated with shock tunnel testing. Transducer rise times on the order of 1 to 5 μsec are not uncommon, and measurement capabilities covering the regime from 0.0005 to 100,000 psi are available. Some designs of piezoelectric pressure transducers may operate in temperature environments from -400 to +500°F. Characteristics of many piezoelectric pressure transducers are listed in (4).

2.5 Force-Balance-Type Pressure Transducers

Force-balance-type pressure transducers (5 and 7) differ from the other types of transducers previously discussed in that they possess a feedback loop which effects a comparison between the electrical output quantity and the pressure input quantity. When the pressure sensing element (usually variable reluctance) tries to deflect in response to an applied pressure, an electrical output signal is generated and fed into a servosystem which supplies the necessary force to maintain mechanical equilibrium of the elastic sensor. Figure 30 shows such a force-balance-type transducer available from Bell and Howell/CEC (87). This system consists basically of two parts: a transducer and a servoamplifier. Known as the Precision Pressure Balance, the transducer contains a bellows for pressure-summing, a frictionless lever and linkage mechanism to connect the bellows to an electromagnetic force coil, and a linear differential transformer. These components are housed in a cast-aluminum case.



(Figure Reproduced through Courtesy of Bell & Howell CEC).

Fig. 30 Force-Balance Pressure Transducer

The servoamplifier acts upon the error signal from the transducer which is produced when the linear differential transformer senses an unbalance caused by pressure applied to the bellows. In response to the error signal, the servoamplifier supplies a proportionate signal to the force coil of the transducer. This current results in an electromagnetic counter-force to the bellows precisely equal to the force arising from applied pressure. The amount of current flowing through the force coil is proportional to the magnitude of applied pressure.

The main advantage of the force-balance-type transducer over conventional transducers is its accuracy. A maximum static error band of 0.05 percent of full scale output is common. This allows the force balance device to be used as a standard pressure monitor for the calibration of many conventional-type transducers. Pressure ranges from 1.5 to 10,000 psi are normally provided, and the operating temperature range is approximately 40 to 165°F.

The force-balance-type transducer is normally limited to static measurements because of the relatively low resonant frequency of the sensor and also because of the pressure input port configuration. The seismic mass combined with the mechanical linkages of the transducer result in high acceleration sensitivity (approximately ten percent full scale per g). The large size and weight of the force balance transducers make it inconvenient for many applications.

In summary, the most effective area of application for the force-balance-type transducer is for extremely accurate measurements of static pressures.

3. MEASURING SYSTEMS

After a transducer has been selected with appropriate characteristics for the application at hand, the remaining elements of the measuring system must be selected. These elements may be generally categorized as being a part of the pneumatic system or as signal conditioning equipment. Equal consideration must be given to the selection of compatible and appropriate equipment for these parts of the measuring system as was given to the selection of the transducer. Therefore, some of the options which are available along with some of their advantages and disadvantages will be presented in the following sections.

3.1 Pneumatic System

Obviously the pressure to be measured must be transmitted to the transducer. This must be done with no alteration of the measured quantity. Therefore, consideration must be given to how the transducer will be mounted, how it will be sealed against pressure leaks, whether the appropriate time response may be obtained, whether thermo-molecular effects are present, etc. Some of the more prominent considerations involved in achieving the aforementioned will be discussed herein.

3.1.1 Transducer Installation

The majority of wind tunnel pressure measurements are associated with model measurements, although numerous other measurements, such as pitot pressure, wall static pressure, stilling chamber pressure, etc., are required; therefore, model installations will be discussed primarily. In a continuous flow tunnel, transducer location is not extremely important in most cases since response times (Section 3.1.2) are not critical. (Two exceptions to this are: 1) when slow response significantly affects the cost of running a test, and 2) when unsteady or transient pressures must be measured.) Therefore, a transducer may be conveniently located outside the tunnel in which measurement is required and connected to the measuring point with pressure tubing (Fig. 31). This permits more measurements to be made on small models than would be possible with transducers mounted internal to the model. It also permits pressure scanning equipment to be used which only requires one transducer for several pressure measurements (Section 3.1.3). The user may also protect the transducer from environmental effects such as temperature and vibration which may exist in the tunnel environs. The transducer is easily accessible for repair, modification, calibration, etc., and there is little or no restriction on the size of the transducer. The basic problem which must be avoided in such an application is that of pressure leaks. This can only be eliminated through care in installation and with careful checkout of the system.

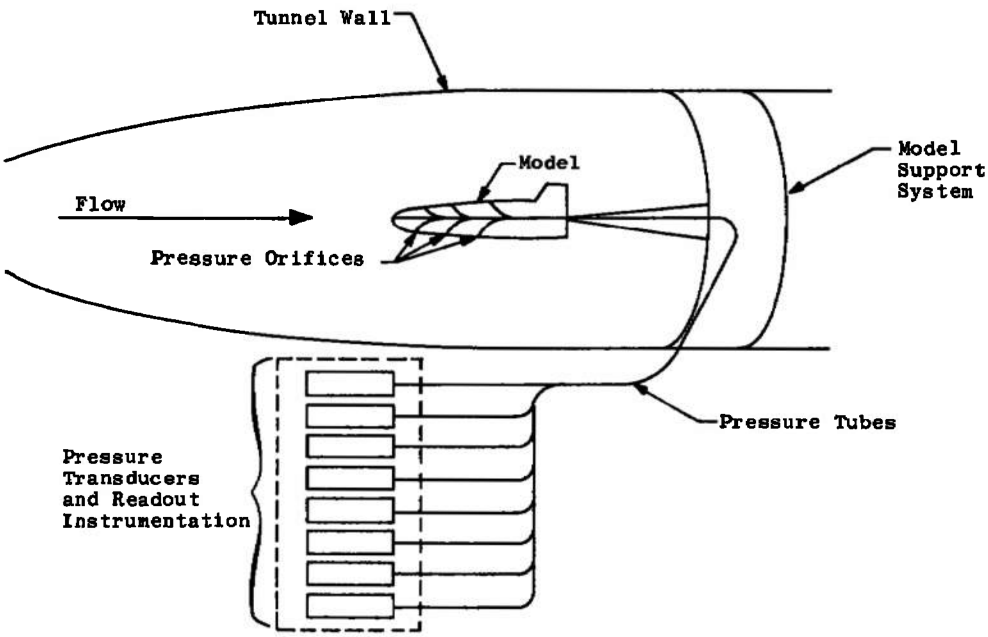


Fig. 31 Wind Tunnel Model Pressure Measurement

When measurements are required in short-duration facilities or when unsteady or transient data are required in continuous tunnels, time response becomes primary in importance. Response time is discussed in Section 3.1.2. For the present discussion, it is sufficient to say that when rapid response is required, the transducer must be exposed directly to the media whose pressure it is desired to measure (flush mounted) or be connected to the measurement point by very short tubing lengths (Fig. 32). (Of course, the transducer must also have appropriate time-response characteristics.) This dictates in

most cases that the transducer be located inside the test model. In many instances this means that the transducer must be protected from effects of temperature, vibrations, and particles in the flow media. These extraneous effects can produce transducer failure, or they can result in interactions which cannot be distinguished from pressure when the data are observed. Various means have been devised for protecting the transducer. For thermal protection, water-cooled transducers are available from many manufacturers (74 and 88) (Fig. 33). Water cooling of the test models or transducer packages is also effective. For transient applications requiring flush mounting of transducers, flexible silicone compounds may be applied to the exposed transducer parts (generally the diaphragm) to delay the heat pulse until steady flow conditions have been reached and the pressure has been measured (89 and 90) (Fig. 34). Recessing of the transducer and bleeding helium past the exposed diaphragm is a useful cooling technique when high frequency response is required in conjunction with long term measurements (89) (Fig. 35).

The effects of vibration are to produce an unwanted oscillatory signal superimposed on the pressure signal developed by the transducer; the transducer and associated pneumatic tubing can also be damaged as a result of vibrations. Some transducers have acceleration compensation as an integral system (Sections 2.2.1, 2.4.1, and 2.4.2); however, in severe shock environments this will not prevent transducer damage, but will only compensate for the effects of vibration on the transducer signal. The use of an accelerometer in an electrical summing circuit can also compensate for vibratory effects (Section 3.2.5) but likewise provides no protection for the transducer. Shock mounting of the transducer in conjunction with one of the above compensating schemes generally provides the optimum performance when in a vibrating environment. A typical shock-mounted installation is shown in Fig. 36. The principle of shock mounting is to make the resonant frequency of the mounted transducer low relative to the disturbing frequency (89). This decreases the transmissibility ratio (91), and consequently the transducer is subjected to lower accelerations. When shock mounting is impractical because of low transducer mass or spacc limitations, it may be possible to mount thc transducer in such an orientation relativc to the direction of the disturbing vibration that the minimum effect is produced on the transducer. In general, the most sensitive acceleration axis of a diaphragm transducer is normal to the diaphragm; sensitivities along other axes are ordinarily much lower.

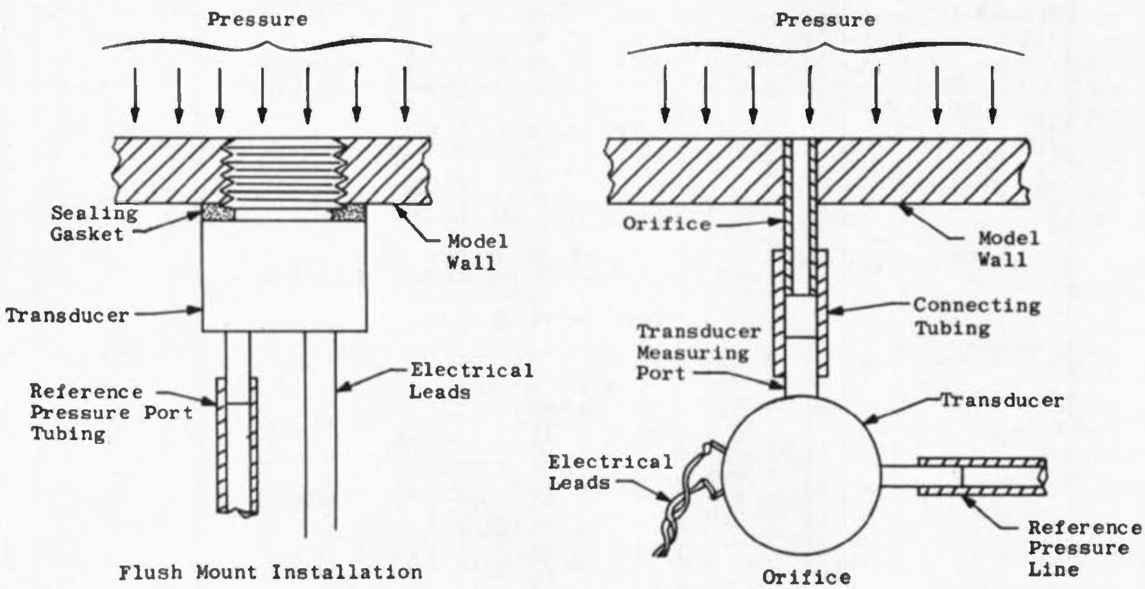


Fig. 32 Transducer Installation

(Figure Reproduced through Courtesy of Kistler Instrument Corporation)

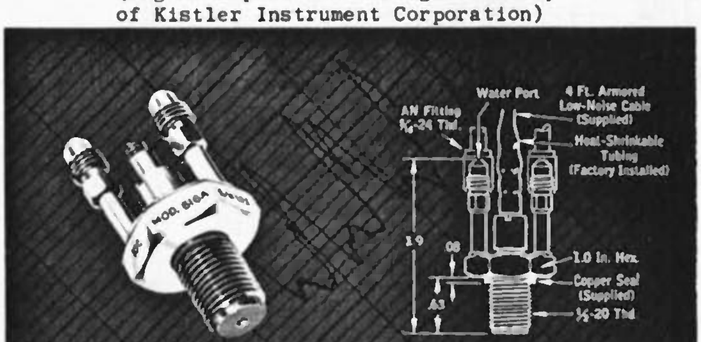


Fig. 33 Water-Cooled Pressure Transducer

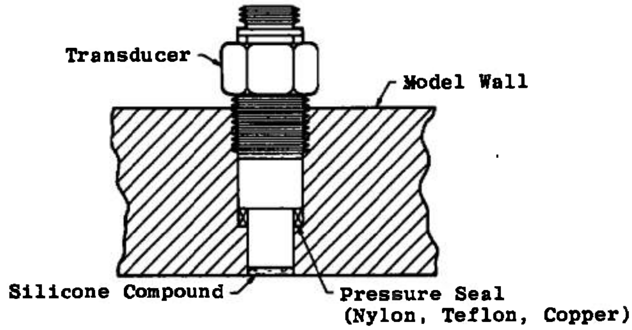


Fig. 34 Flush Mount Pressure Transducer with Thermal Protection (Silicone Compound)

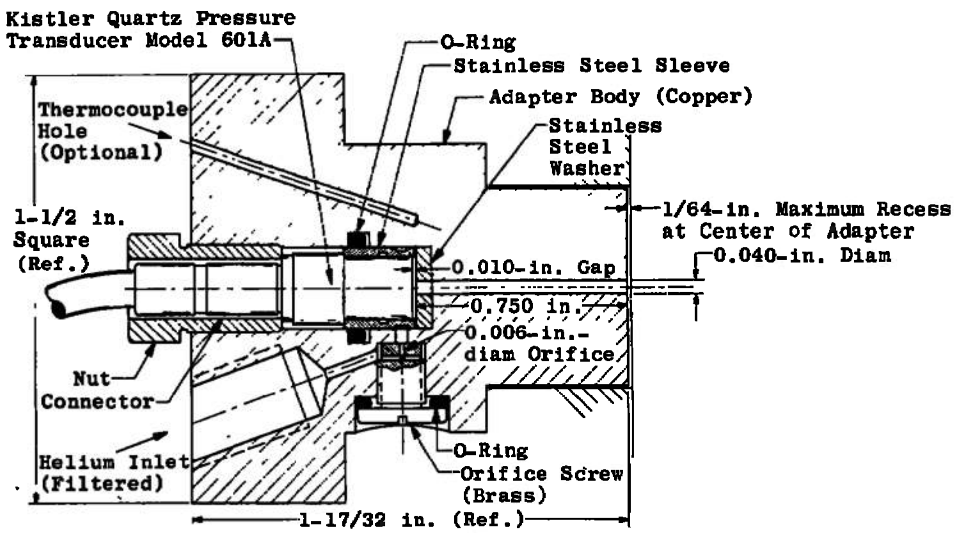


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Fig. 35 Helium-Bleed Technique

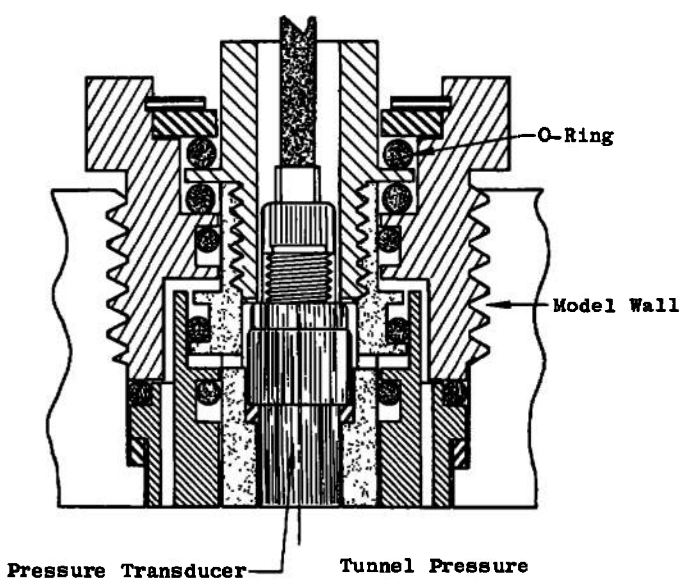

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Fig. 36 Shock Mounted Pressure Transducer

Transducers which must be flush mounted can be sealed in a variety of ways. Of course, sealing techniques vary widely, depending on the pressure level, temperature, vibration, etc. Since most flush-mount applications are for transient measurements, thermal protection is generally provided by a silicone compound which does not interfere with any seal desired and anti-vibration mounts generally are designed to provide a pressure seal along with their vibration isolation components (89). For reasonably low pressures and small exposed transducer areas, either epoxy cements or silicone compounds may be used to mount the transducer as shown in Fig. 37. Some experimenters recommend rigid mounting (90 and 92) while in some applications where model stresses may be transmitted to the transducer case with a rigid mount, soft mounting is superior. For higher pressures than cements are capable of withstanding, seals similar to that shown in Figs. 34 and 38 are employed (74).

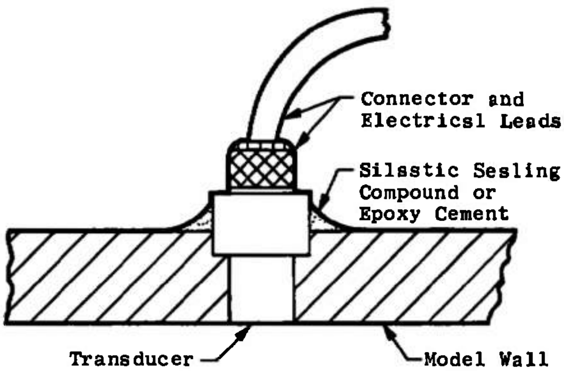

Fig. 37 Low Pressure Transducer Installation and Pressure Sealing Technique

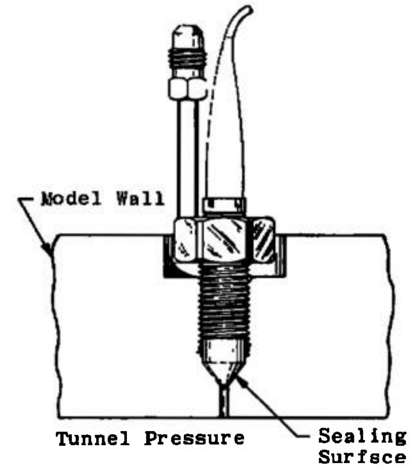

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Fig. 38 High Pressure Transducer Installation and Sealing Technique

Flush-mounted transducers are extremely vulnerable to impact damage from high velocity particles in the flow media. Methods of protecting the transducer from particle impingment have been developed [(90 and 92) and (Fig. 39)]; however, in general, it may be said that protective devices degrade frequency response and response time. In such cases, a compromise is required between the minimum acceptable response and the transducer protection required.

3.1.2 Time Response of Pressure Measuring Systems

Response time is defined as the time for the pressure measuring instrument to reach a given percentage of the applied pressure (generally 99 percent) when a step pressure is applied to the system. Various factors affect response time: the transducer mounting configuration, the volume of the measuring transducer, the geometry of the tubing connecting the measuring orifice and the transducer, the pressure levels or flow regime, the transducer natural frequency and damping, and, of course, the response of the recording instrumentation. The response time of a pressure measuring system increases as the pressure to be measured decreases and thus becomes increasingly important in high speed, short duration, wind tunnels (93). The investigation of response time problems is necessary in order to derive the optimum measuring and tubing systems to fully exploit the capabilities of wind tunnels, and in limiting cases, to ensure that the pressure in the measuring transducer reaches equilibrium with the orifice pressure within the tunnel operating time.

There are many pieces of appratus for determining the response time of a pressure measuring system. Several are described in Section 4 of this report. Sometimes it is desirable to know the frequency domain response of a measuring system. Section 4 describes techniques for determining this from step function calibrations as well as directly using frequency domain calibrators.

3.1.2.1 Flush-Mounted Transducer Response

In short-duration facilities the transducers must, at times, be flush mounted or only slightly recessed in order to respond during the test period. Of course in a flush-mounted installation, response time is determined by the transducer's characteristics of resonant frequency, f_n, and damping ratio, h, according to the equation

$$t_p = 1/(2f_n \sqrt{1 - h^2}) \qquad (1)$$

where t_p is defined as the time to the first peak for an undamped transducer (Fig. 40). Most transducers whose resonant frequency is high enough for short-duration facilities are essentially undamped, and the starting shock of the tunnel excites the transducer and it "rings" at its resonant frequency throughout the tunnel run time (Fig. 40). This ringing makes it difficult to reduce the pressure data, and it is desirable to electronically filter this ringing to give a smooth data trace as in Fig. 41. With the addition of the filter (either low pass or notch filters are generally used), the system response is generally determined by the filter characteristics rather than the transducer. At times a compromise must be made between the amount of ringing which can be tolerated on the pressure signal and the minimum rise time which can be tolerated since increasing the filtering also increases the system rise time.

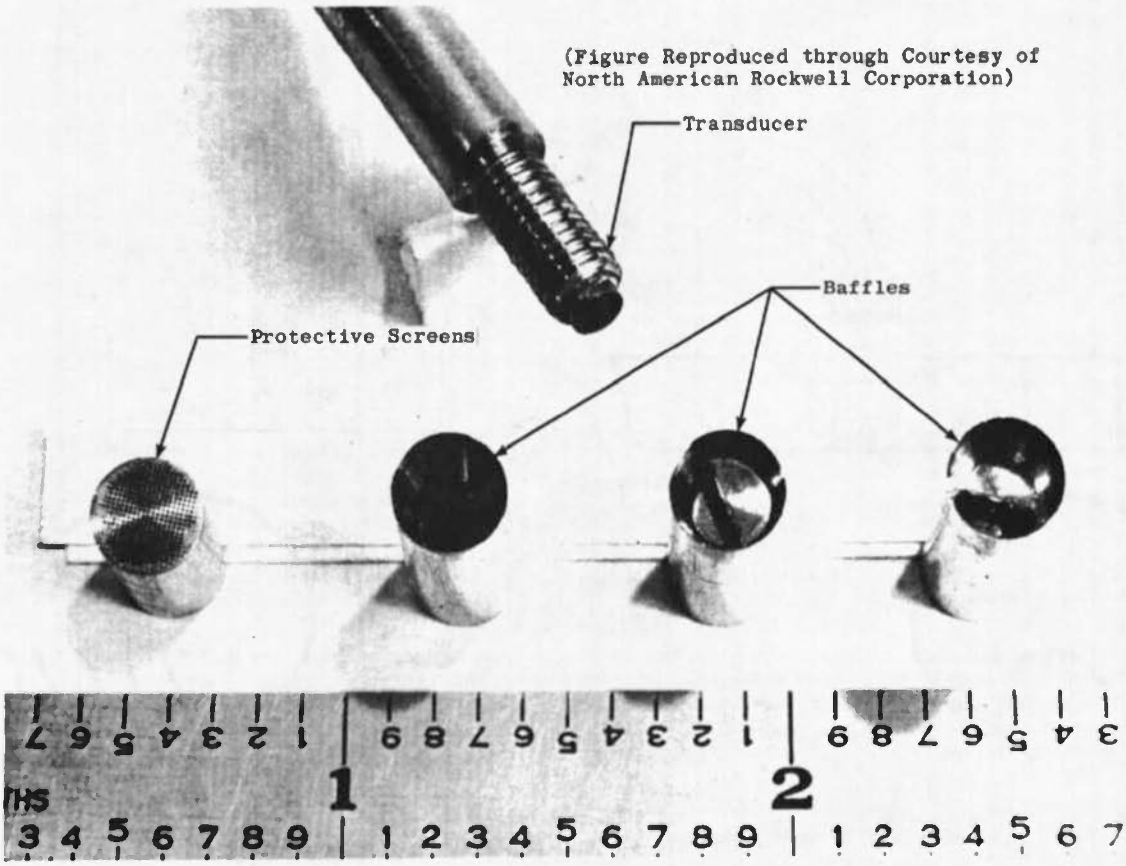

Fig. 39 Transducer Diaphragm Protection Devices

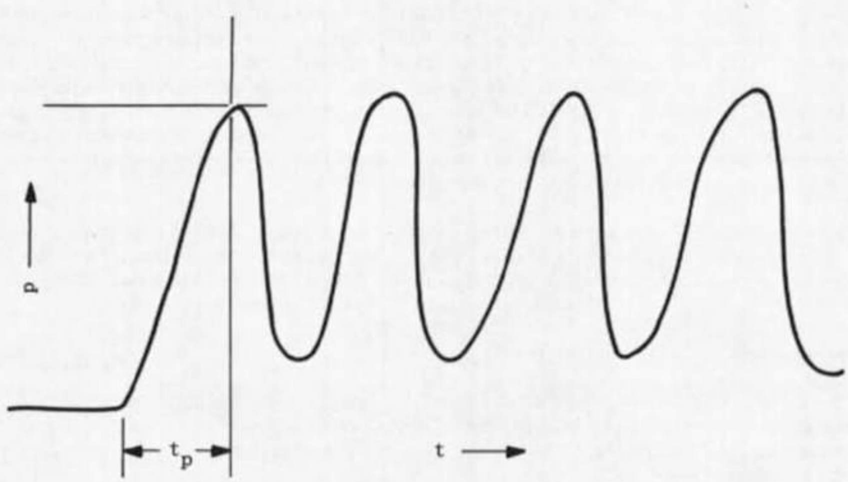

Fig. 40 Unfiltered Pressure Transducer Data Trace

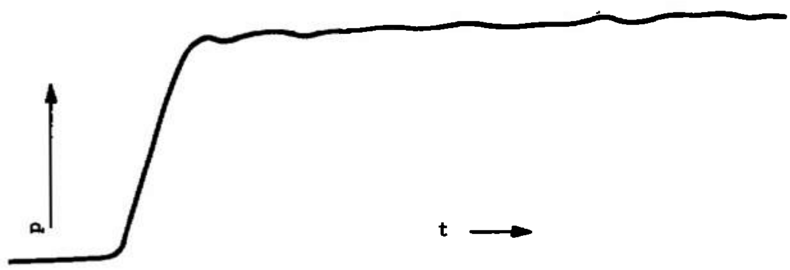

Fig. 41 Filtered Pressure Transducer Data Trace

The resonant frequency of a flush-mounted transducer and its transient performance are easily determined in a shock tube (89 and 94) or with fast-acting valves (95). Evaluation of the system performance with filters included can be performed with the same pneumatic setup.

The response of transducers which are recessed (Fig. 42) or covered with protective baffles (Section 3.1.1) can also be determined with the shock tube or fast-acting valves. One of the primary factors to consider when recessing transducers is the organ pipe effect of the recessing cavity. The frequency of this cavity is given by (38):

$$f = \frac{a}{4\ell} \qquad (2)$$

where

a = acoustic velocity of the medium being measured in ft/sec (1100 ft/sec for air and 3000 ft/sec for helium at 25°C)

and

ℓ = cavity length in ft

This frequency is oftentimes low enough to be troublesome in a highly transient measurement (test times on the order of 1×10^{-3} sec) and cannot be filtered electronically without increasing the system response time intolerably.

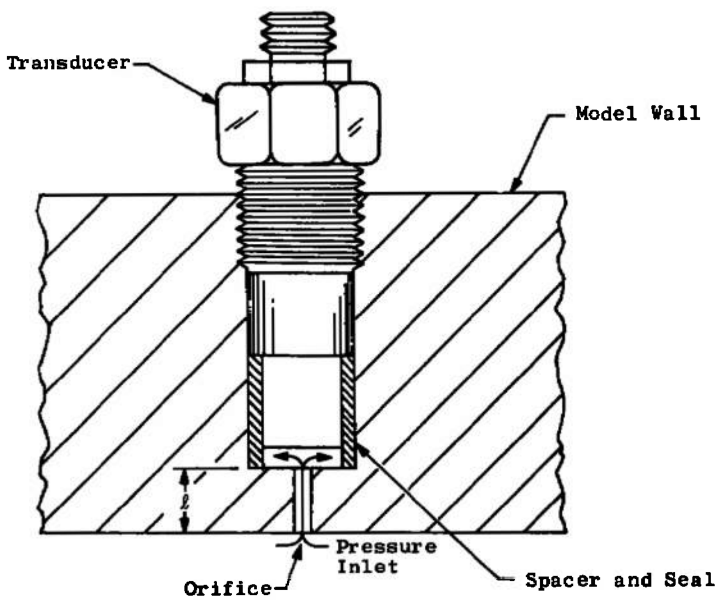

Fig. 42 Recessed Pressure Transducer Mounting Technique

3.1.2.2 Response of Systems Employing Tubulation

Installations which utilize tubulation to connect the measuring orifice to the transducer are generally found in facilities where the test times are measured in seconds or minutes since response times of such systems are long. There are notable exceptions; the pressure measuring systems used in hotshot tunnels utilize short tubes between transducer and orifice, and test times and response times are in the millisecond range (Figs. 43 and 44) (51 and 96). In a system which uses tubulations, it is necessary to know the response time in order to determine whether sufficient test time is available and to determine what tunnels testing procedures must be employed. In many quasi-continuous or continuous facilities, pitch and pause operations are utilized, and response times must be determined to ensure pressure stabilization at each pitch angle. Several reports are available describing the time response of pressure

measuring systems in the various flow regimes and with various tubing systems (97, 98, 99, 100, 101, and 102). Some of the more recent reports incorporate computer programs which permit rapid computation of response times which would be quite laborious if done by hand calculation. A report by Cain (103) provides a program which can be used with a variety of tubing systems for any flow regime (viscous, transition, or molecular) which may be encountered. The program is not written so as to provide direct optimization of a tubing system, however, it readily lends itself to parametric studies which can be used to optimize tubing geometries for given initial tunnel pressures and pitch angles, direction of pitching, and the required pause time for pitch and pause operation. Pick (104) has developed a computer program which is useful for the most common configuration of a pressure measuring system (two tubes of different diameters and lengths connecting an orifice to a constant volume transducer). It should be noted that detailed design of pressure measuring systems depends to a large extent on experimental data for the response times because the theory cannot provide extremely accurate predictions (93).

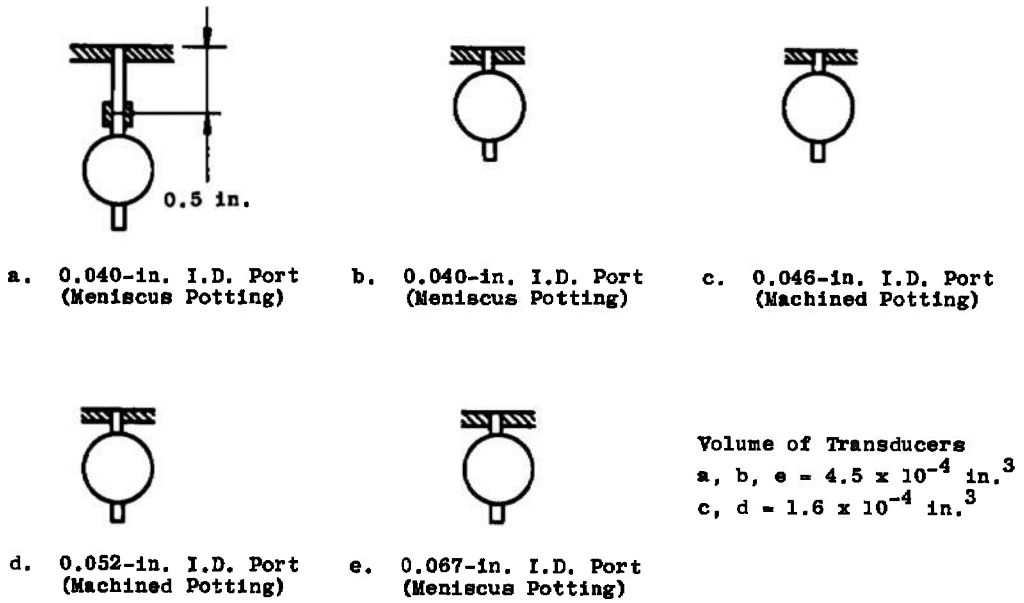

Fig. 43 Response Study Configurations of Low Pressure Variable Reluctance Transducer

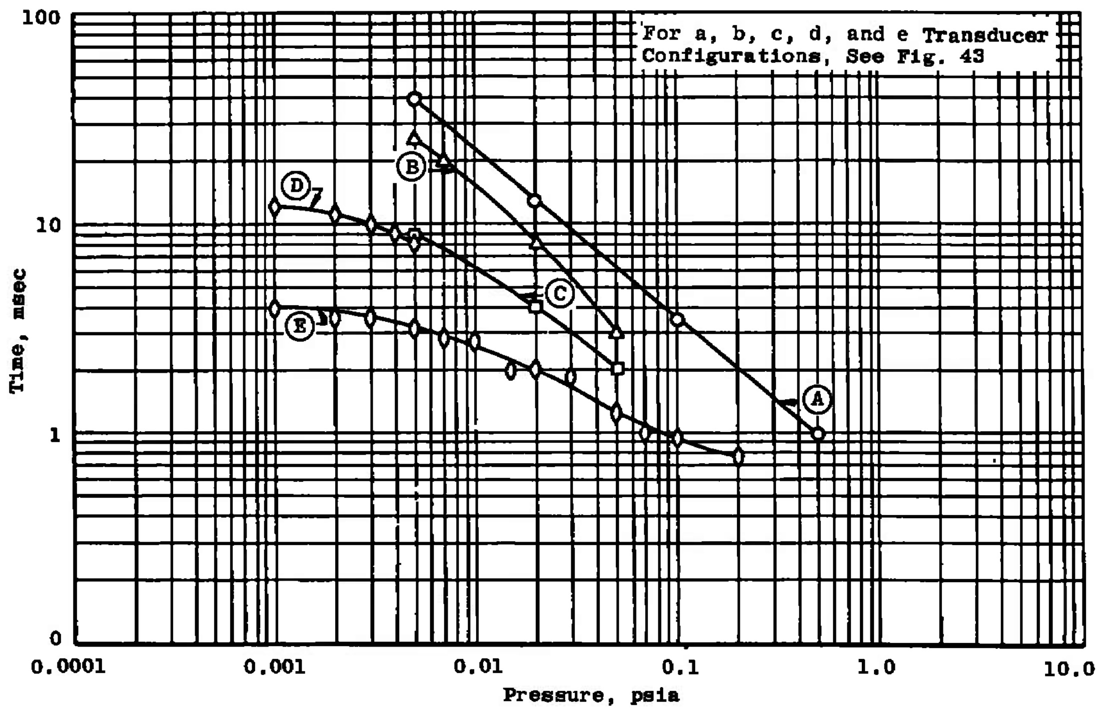

Fig. 44 Low Pressure Variable Reluctance Transducer Response Time (Time Required to Reach 95% of Final Value)

Some general rules which should be observed in designing a pressure measuring system with minimum response time are 1) the orifice diameter should be more than one-half the model tubing diameter; 2) the model tubing should be made as short as possible, incorporating the largest feasible inside diameter; and 3) the volume of the pressure transducer should be minimized. It should also be noted that in general the advantage of pumping the initial line pressure to a value close to the model-surface pressure is quite small (105).

The large number of parameters which affect response time in a system using tubes (tube diameter and length, number of tubes, transducer volume, viscosity, pressure level, etc.) makes it difficult to provide a generalized approach for determining response time; however, an equation developed by Kendall (106), Bauer (107), Pick (104), and Larcombe and Peto (93) provides a fairly good approximation for a one-tube system in pressure ranges from 0.01 psia to 1 atm:

$$t = \frac{128\,\mu \ell V}{\pi d^4 g_c p_2} \; \ell n \; \frac{(p_o - p_2)(p + p_2)}{(p - p_2)(p_o + p_2)} \tag{3}$$

where

t = time, sec
d = tube diameter, cm
g_c = conversion factor = 1.333
p_2 = pressure applied to tubing system, mm Hg
p_o = initial pressure in tubing system, mm Hg
p = pressure at time t, microns
ℓ = tube length, cm
V = volume of tubing and measuring transducer, cm^3
μ = viscosity, poises (1.8×10^{-4} for air)

This expression was developed for the conditions that the flow is isothermal, that the Reynolds number based on tube radius is less than 1000 (Poiseuille flow), that no slip flow is involved, that the system volume remains constant, that pressures in the tubing are always in quasi steady-state, and that pressure disturbances are propagated with infinite velocity (inferring that the time required for the flow to become fully developed is small compared to the response times under consideration).

This equation can be extended to the case of a compound tubing system comprised of various tube diameters and lengths. This is done by considering an equivalent system of length ℓ_e of constant diameter tubing d_1 where ℓ_e, is given by

$$\ell_e = \ell_1 + d_1^4 \sum_{i=2}^{n} \frac{\ell_i}{d_i^4} \tag{4}$$

where ℓ_i and d_i are the length and diameter of the i^{th} tube. Orifices are treated as another tube in the system. Of course, the volume of the system is altered with the addition of tubes, and the actual volume of the tube system must be used in Eq. (3).

This theory predicts the correct trends for the variation of response time, but errors as large as 100 percent may appear in the absolute values. The theory was developed on the assumption that the measuring instrument has a finite volume and that the complete tube volume can be considered to be concentrated at the end of the tube adjacent to the instrument; obviously, this assumption produces an error when the instrument volume approaches zero.

Figure 45 shows a plot of stabilization times as a function of pressure tube length and diameter, and system volume for a simple one-tube system.

In continuous tunnels where extensive pressure scanning equipment is used, automated systems have been developed, e.g., VKF/AEDC, which detect pressure stabilization by checking the differences between consecutive samples from the same orifice. When stabilization has been reached, the data are recorded and the system steps to the next orifice. Large time savings are realized by such a system.

3.1.3 Pneumatic Switching

Continuous monitoring of large numbers of pressure orifices required in many wind tunnel installations presents two basic problems: 1) transducers and signal conditioning equipment become very expensive when one unit of each is required for each measurement and 2) maintenance and calibration procedures become more complex and time consuming as the number of measurements increases. Both of these problems may be alleviated through pneumatic switching. Pneumatic switching is an elementary concept; a number of tubes from various measurement locations are routed to a common point and then applied individually to a common transducer and readout system as shown in Fig. 46. Systems for achieving this switching function can vary from very simple manually operated valves to elaborate and

complex electromechanical devices which scan automatically at high rates of speed. Several advantages are provided by pneumatic switching; they can be summarized as follows (108):

1. It enables a number of pressures to be scanned by one transducer, thus reducing the complexity and cost of the system.
2. It allows the transducers to be switched to set reference pressures or to a vacuum to check calibration and zeros.
3. By subjecting the transducer to a vacuum (or to a selected pressure) between measurements, the effects of hysteresis in the measurement can be eliminated.
4. It produces more accurate results when pressure differences or comparisons are required since only one transducer calibration constant is involved in the data reduction.

To fully exploit these advantages the scanning switch must meet the following requirements:

1. Introduce the minimum possible extra volume to the pneumatic system.
2. Avoid leaks between the pressure lines and atmospheric or reference pressures over its working range.
3. Minimize any pumping of the pressure lines during the switching operation.
4. Be capable of remote control.
5. Be capable of carrying more than one transducer and preferably to accept more than one type.
6. Be reliable and require little maintenance.

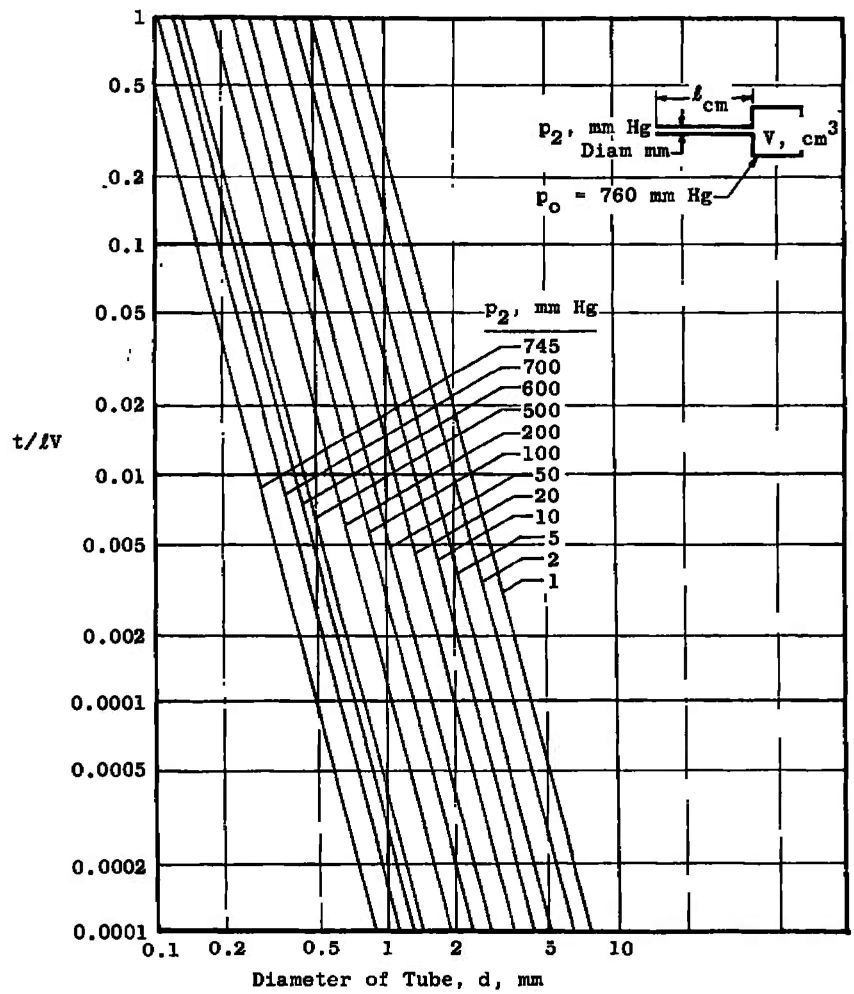

Fig. 45 Stabilization Time (to One Percent) of a Pressure System (from Ref. 106)

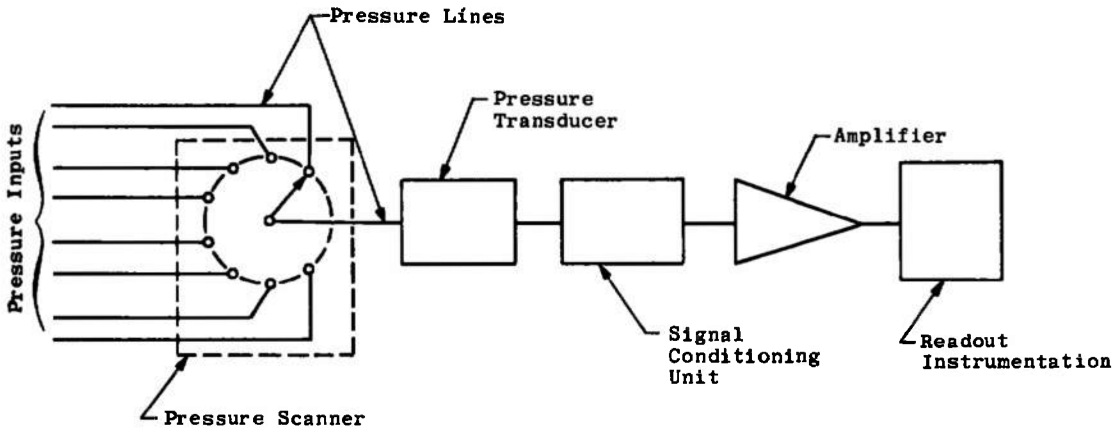

Fig. 46 Basic Pressure Scanning System

There are several commercial switches available (e. g., from Scanivalve, Inc., Box 20005, San Diego, California 92120, Giannini-Voltex (Datex Division), 12140 E. Rivera Road, Whittier, California 90606, Solantron, United Kingdom). The Jet Propulsion Laboratory in Los Angeles, California, the National Physical Laboratory in Great Britain, and the Ballistic Research Laboratory in Maryland have designed their own switches (109, 110, and 111). Typical specifications of these switches are as follows:

Number of input ports	12 to 64
Number of output ports	1
Leak rate	< 0.5 in. Hg per hour
Scanning rate	6 to 40 ports per second
Input pressure range	0 to 500 psi

Figures 47 and 48 show details of the switch developed by the National Physical Laboratory.

The two problems which are most frequently encountered with pressure switches are leaks and degradation of response times. Leaks generally occur as a result of wear and are accelerated by the presence of abrasive particles in the media being measured. Some switches utilize O-rings for seals to provide easy maintenance when leaks develop (108 and 109).

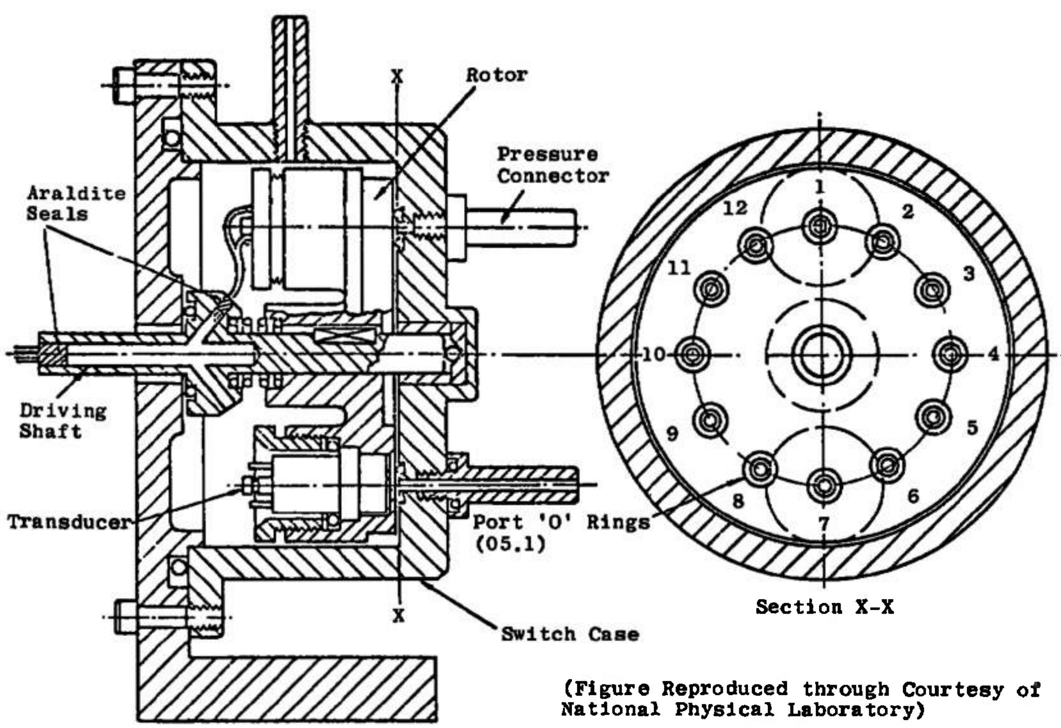

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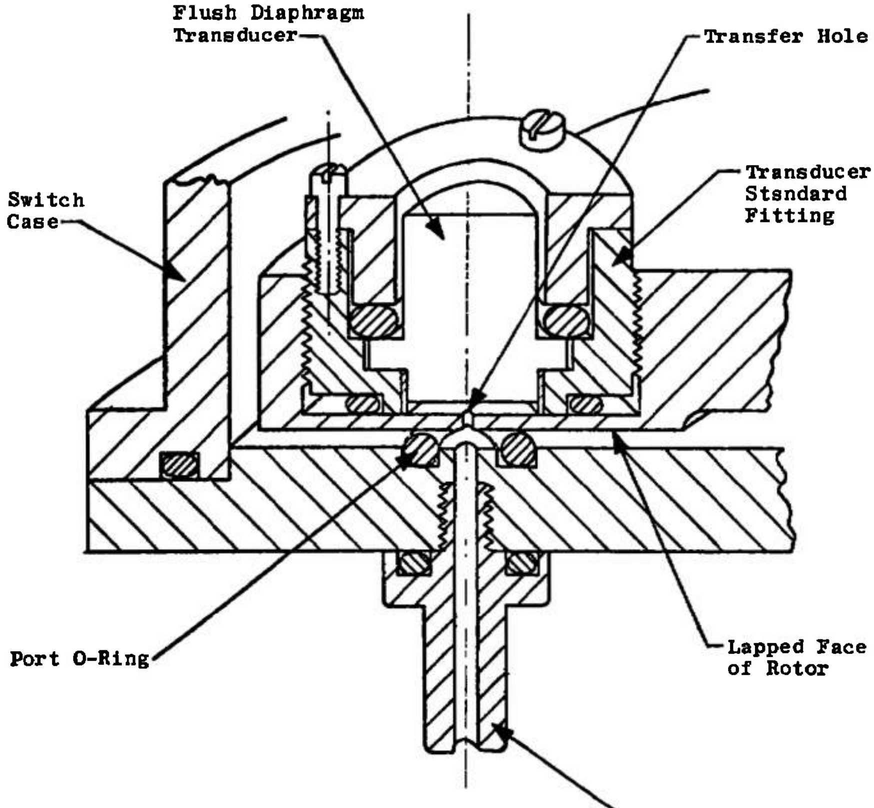
Fig. 47 12-Way Pressure Scanning Switch



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National Physical Laboratory)

Fig. 48 Section Showing Standard Transducer Fitting Mounted in Rotor of Pressure Scanning Switch

It must be recognized and accepted from the beginning that a longer time will be required to measure a given number of pressures when utilizing a pressure switch than utilizing a system with one transducer per measurement point. However, if this basic compromise is made, then methods for reducing measurement times to a minimum can be pursued. Response time of the tubing system has been discussed previously in Section 3. 1. 2. 2; it remains to optimize the additional time delays created by the pressure switch. To maximize the scan rate which can be achieved, the volume between the scanner pressure transducer diaphragm and the surface where the pressure is being scanned must be minimized and any connecting passageways and orifices must be as large as possible. The volume in a typical switch developed by the National Physical Laboratory is 0. 0004 in.^{3}. Response times for this switch relative to pressure level are shown in Fig. 49.

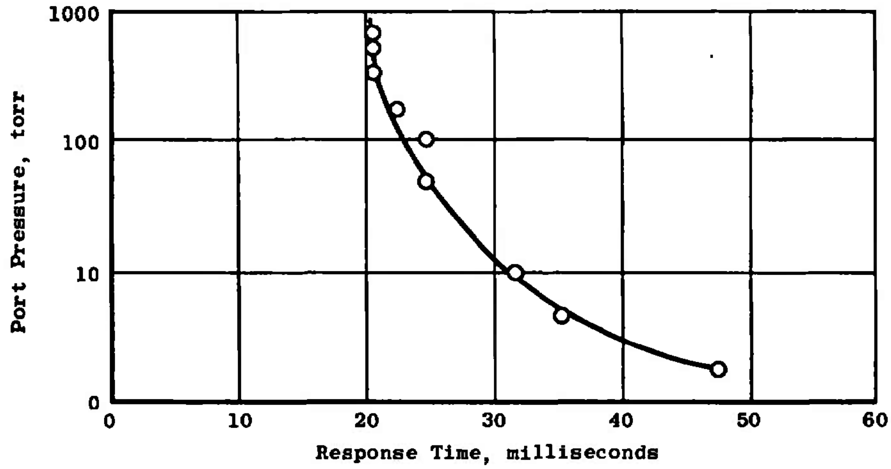

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Fig. 49 Response Time of 48-Way Switch Measured to 99. 5 Percent of the Applied Port Pressure

Now consider the total time, T, required to scan n ports from the initiation of a tunnel run (93). The transducer will be at rest on port 1 during the time, t_o, required for all the tube systems to reach equilibrium with the measured model pressures. Ports 2 to n remain to be scanned and each will have a response time, t_t, once the transducer is registered with it. There will be (n - 1) travels between ports, each taking time t_i, and n recordings, each taking time t_r. Thus,

$$T = t_o + (n - 1) t_t + (n - 1) t_i + nt_r \tag{5}$$

Figure 50 shows the pressure-time profile of the transducer during a tunnel run.

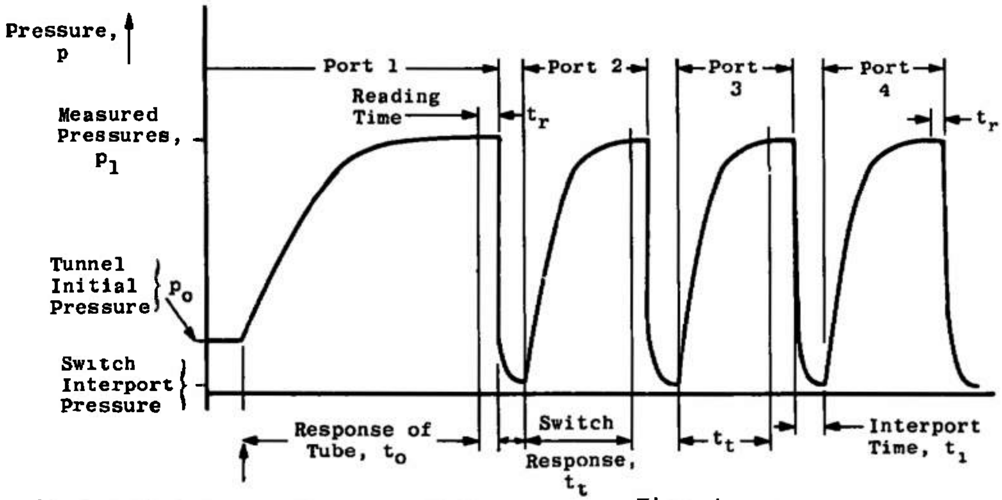

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Fig. 50 Pressure-Time Profile of Transducer in Scanning Switch with Similar Tube Systems Connected to Tunnel

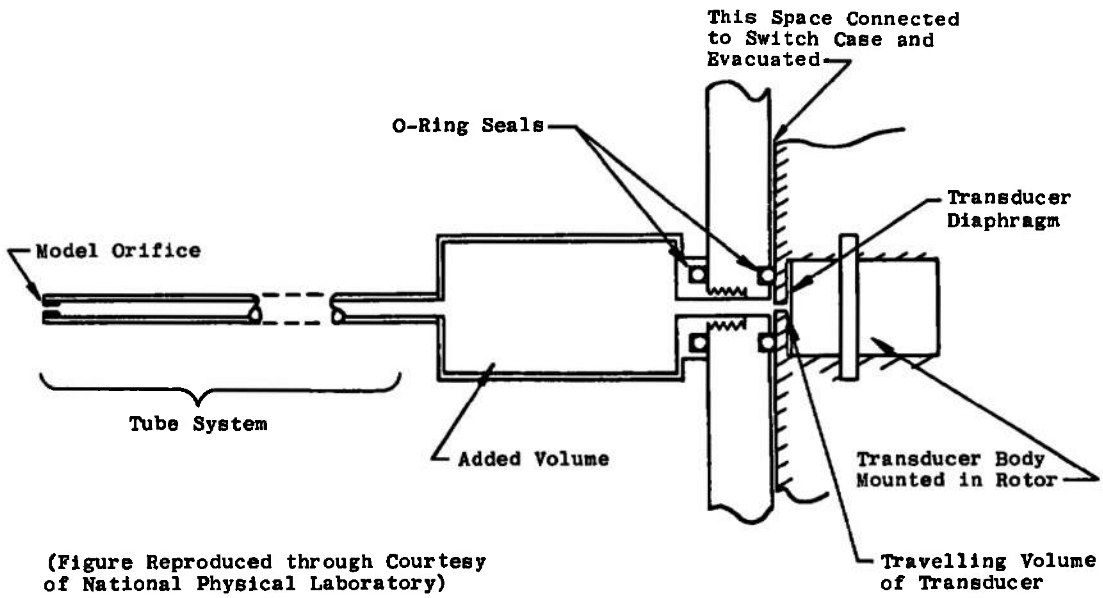

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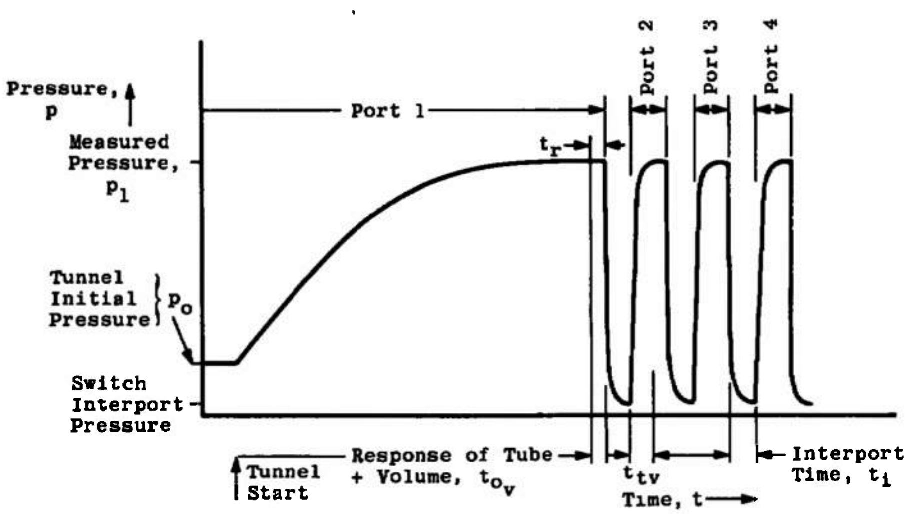
Fig. 51 Method of Attaching Added Volume to Switch Port and Tube System

The total time, T, required to scan n ports can be reduced if n is large by placing volumes immediately in front of the switch ports (Fig. 51) to isolate the switch from the effect of the tubing resistance (93). If the added volumes are made 1000 times the traveling volume of the transducer, then the error attributable to sampling by the transducer will be approximately 0.1 percent after the response time of the switch in isolation as defined in Fig. 49. The addition of a volume to the tube system increases the time, t_o, for the pressure in the tube to reach equilibrium with the measured pressure, but the time, t_t, required to sample this pressure with the scanning switch is decreased because of the isolation from flow resistance effects in the tube. The pressure-time profile of the transducer for tube systems with volumes attached to the switch is shown in Fig. 52, which can be compared with Fig. 50 for similar tube systems connected directly to the switch.



(Figure Reproduced through Courtesy of National Physical Laboratory)

Fig. 52 Pressure-Time Profile of Transducer in Scanning Switch with Similar Tubes Systems plus Volumes Connected to Tunnel

For a system with volumes, Eq. (5) is modified to

$$T_v = t_{ov} + (n - 1)\, t_{tv} + (n - 1)\, t_i + nt_r \tag{6}$$

where suffix v indicates the addition of volumes to the tube systems, and time t_{tv} is the same as the response time of the switch in isolation.

Thus, by setting $T = T_v$ we can find a value of n beyond which the total time will be reduced by the addition of the volumes; for smaller numbers of tubes the time will be increased. It is important to take advantage of the added volumes for large values of n for both intermittent tunnels (to increase the number of readings that can be made in a given operating time) and for continuous tunnels (to decrease the operating time for a given number of readings and hence to economize).

In order to minimize time delays, some systems employ automated stepping circuitry which samples the pressure indicated by the scanner transducer to determine when stabilization occurs and then signals the scanner to step to the next position.

It is, in general, standard practice to apply calibration pressures on appropriate scanner ports to permit calibration of the pressure transducer during each scan cycle (112).

3.1.4 Thermo-Molecular Effects

When pressures are measured under rarefied flow conditions, there are some thermal effects which can seriously affect measurement accuracy. These effects are variously classified as "thermal transpiration," "thermal diffusion," "thermal creep," or more generally, "thermo-molecular pressure" (113, 114, and 115). When a temperature gradient exists along a sensing tube and/or when there is heat transfer at a sensing orifice, the "thermo-molecular" phenomena may introduce sizable errors. For an infinitely small orifice in a surface subject to heat flux, the theoretical relationship between the pressure measured by the orifice, $(p_i)_{d \to 0}$, and the true normal force per unit area, (p_w), is (116)

$$\frac{(p_i)_{d \to 0}}{p_w} = \frac{2}{\sqrt{\left[1 - \dfrac{2\sqrt{2\pi}\,\dot{q}\,(\gamma - 1)}{\alpha (p_i)_{d \to 0}\sqrt{(RT_w)}\,(\gamma + 1)}\right]}} + \sqrt{\left[1 - \dfrac{2\sqrt{2\pi}\,\dot{q}\,(\gamma - 1)(1 - \alpha)}{\alpha (p_i)_{d \to 0}\sqrt{(RT_w)}\,(\gamma + 1)}\right]} \tag{7}$$

where the variables $\dot{q}$, γ, α, and T_w are the heat flux to the surface, the ratio of specific heats, the thermal accommodation coefficient, and the surface temperature, respectively. The thermal accommodation coefficient is defined as

$$\alpha = \frac{T_g^- - T_g^+}{T_g^- - T_w}$$

where T_g = temperature of the gas molecules and T_w = temperature of the model surface in which the orifice is located. The superscripts - and + refer to gas molecules incident to the model and molecules reflected from the model surfaces, respectively. Experimental data have shown that the pressure indicated by a finite sized orifice p_i, for four gases, H_2, He, N_2, and Ar, may be represented by

$$\frac{p_i - (p_i)_{d \to 0}}{p_w - (p_i)_{d \to 0}} = \frac{0.3148(M^{1/8}/Kn_{w,i,d})^{1/2} + 0.01478(M^{1/8}/Kn_{w,i,d})^2}{1.0 + 0.3148(M^{1/8}/Kn_{w,i,d})^{1/2} + 0.01478(M^{1/8}/Kn_{w,i,d})^2} \tag{8}$$

In order to correlate the data for the various gases, it is necessary to include the molecular weight, M. $Kn_{w,i,d}$ is the Knudsen number based upon the wall temperature, indicated pressure, p_i, and the orifice diameter, d. Equation (7) is used to determine $(p_i)_{d \to 0}$. The experimental and theoretical results are combined into a single semi-empirical nomograph in Fig. 53.

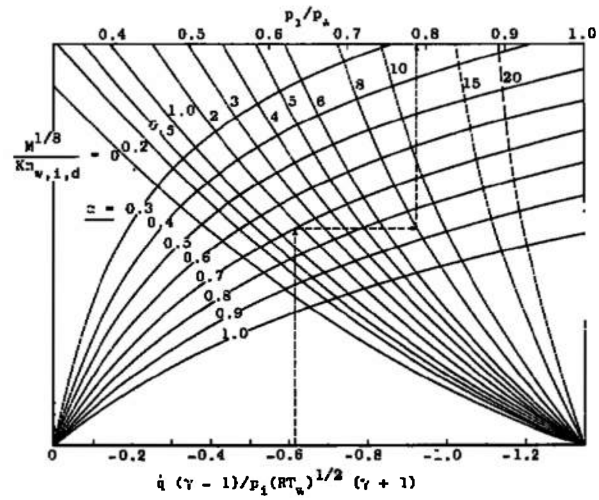


Fig. 53. Nomograph for Thermo-Molecular Pressure Correction at Orifices

The thermo-molecular effect in circular tubes has been investigated using the same four gases and with tubes of various lengths and diameters (116). The results for these gases and tubes are represented by the following equation:

$$\left[\frac{1 - (T_1/T_2)^{1/2}}{1 - (p_1/p_2)}\right]^{1/2} = 1 + \frac{0.275}{Kn_1}\left(\frac{T_1}{T_2}\right)^{2/3} + \left[\frac{0.525}{Kn_1}\left(\frac{T_1}{T_2}\right)^{2/3}\right] \Bigg/ \left\{1 + 24.0\left[\frac{1}{Kn_1}\left(\frac{T_1}{T_2}\right)^{2/3}\right]^2\right\} \tag{9}$$

The subscripts 1 and 2 refer to the conditions at the ends of the tube, e. g., the subscript 1 would refer to the end of the tube where the pressure is known. Equation (9) is plotted in Fig. 54 to facilitate thermo-molecular corrections in tubes.

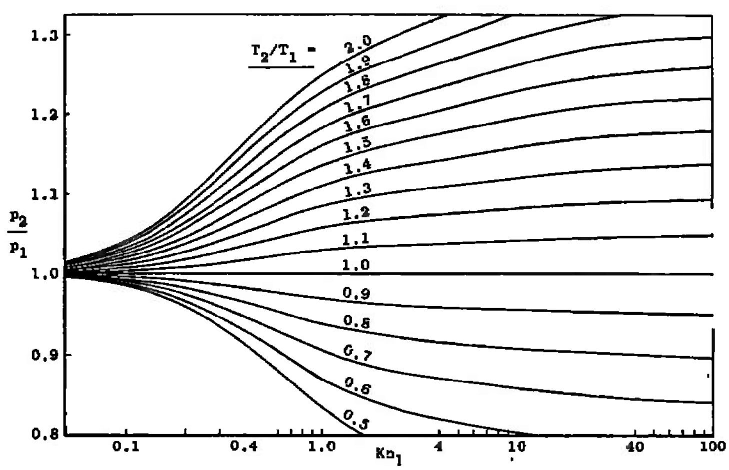


Fig. 54 Curves for Thermo-Molecular Pressure Corrections in Tubes

3.2 Signal Conditioning

Signal conditioning is a widely used and loosely defined expression which has a wide variety of interpretations; however, in the following discussions, signal conditioning will be defined as those processes which transform the electrical signal from a pressure transducer into a form acceptable to its data recording instrumentation. Circuits required for excitation; zeroing, ranging, calibration, noise suppression, filtering, impedance matching, and amplification are among those included in this definition. This equipment is of necessity quite diverse in nature since there is such a wide variety of transducers (Section 2) and data recorders (Section 3.2.7) in use and since a variety of functions is required of the signal conditioners. This makes it impractical to attempt to describe in detail all the signal conditioning instrumentation presently in use. Therefore, it will be the purpose of this section to discuss in somewhat general terms the basic approaches used for conditioning signals from the most widely used types of transducers.

3.2.1 Variable Resistance Pressure Transducer Signal Conditioning

Probably the most widely used pressure transducer in wind tunnel measurements is the strain-gage transducer. The potentiometric transducer also falls into this category of variable resistance devices. Pressure transducers that employ the strain gage as the basic sensing element constitute well over half of all of the pressure transducers used. The output signal from both of these types of variable resistance transducers is a function of the externally supplied power or excitation as well as the pressure being measured. In this regard, they can be looked upon as proportional voltage dividers where the proportions are determined by the pressure input (117).

The excitation source is generally a DC voltage (or current) although this is not necessarily the case; it can be AC. Carrier-type conditioning systems for variable resistance sensors have been used very effectively for a number of years, utilizing carrier frequencies from as low as 60 Hz to as high as 20 kHz. Because of the general superiority of DC signal conditioning for strain-gage pressure transducers, the present use of carrier systems is generally limited to conditioning signals from variable reluctance and linear variable differential transformer transducers. Therefore, the carrier system will be discussed in Section 3.2.2; some of the advantages and disadvantages of the system will be mentioned here.

Advantages:

1. Does not require a low level DC amplifier
2. Has good noise rejection at frequencies outside the band pass of the AC amplifier
3. Has good DC stability; however, not as good as the better DC amplifier now available

Disadvantages:

1. Poor noise rejection at frequencies near the carrier frequency
2. Poorer accuracy than a high quality DC system. A carrier system can generally be expected to give approximately one percent accuracy.
3. Lower frequency response than wide band DC system; generally approximately one-fifth of the carrier frequency.

Two problems stand out in conditioning signals from strain-gage pressure transducers. In the first place, the strain information is represented by a resistance change that is quite small compared with the unstrained resistance. Secondly, the strain sensitivity of the gages is not necessarily the only significant resistance variation function. The thermal coefficient of resistance can cause changes as large or larger than the strain changes.

The most commonly employed circuit to minimize these effects is the simple Wheatstone bridge. The bridge circuit accomplishes the primary goal of getting a data zero for the rest or initial condition of all active elements, and it discriminates against equal resistance changes by all or by adjacent elements.

3.2.1.1 Bridge Equations

Figure 55 is a schematic of a full-bridge transducer in a Wheatstone bridge configuration. The analysis and equations which follow are a summary of the Wheatstone bridge circuit as applicable to strain-gage transducers (118). The transfer function is most conveniently expressed as an output-to-input ratio. Thus, for constant voltage excitation, the equations will be expressed in output volts per input volt.

The general equation for the circuit in Fig. 55 is

$$\frac{e_o}{V} = \frac{\Delta R(1 + A)H}{4\left[R + 0.5\Delta R(1 - A)\right]} \tag{10}$$

where

A = fraction of activity for partially active legs, can take on values from 0 to 1.

H = number of active halves of bridge (referred to the input leads, either 1 or 2)

Equation (10) may be used to analyze any possible bridge configuration. For convenience, it is rewritten below for two common transducer configurations. For a single-active-leg bridge with positive ΔR resistance change,

$$H = 1,\ A = 0$$

$$\frac{e_o}{V} = \frac{\Delta R}{4(R + 0.5\,\Delta R)} \tag{11}$$

For a fully active transducer,

$$H = 2,\ A = 1$$

$$\frac{e_o}{V} = \frac{\Delta R}{R} \tag{12}$$

In the above equation, a positive ΔR indicates an increase in resistance with applied load, whereas a negative ΔR indicates a decrease in resistance with applied load. For approximate calculations, the ΔR term in the denominator may be neglected, thereby simplifying the equations. It should be noted that, for the fully active transducer, the denominator ΔR term disappears. In other than fully active transducers ($A \neq 1$), the denominator ΔR term causes a non-linear variation of electrical output with the pressure input.

For constant excitation voltage, closed or loaded output circuit applications, the transducer can be considered a voltage generator with a source resistance as shown in Fig. 56.

For a voltage measurement device,

$$\frac{e_y}{V} = \frac{e_o}{V}\left(\frac{R_y}{R_o + R_y}\right) \tag{13}$$

For a current measuring device,

$$\frac{i_y}{V} = \frac{e_o/V}{R_o + R_y} \tag{14}$$

3.2.1.2 Balancing Circuits

One of the considerations that leads to the selection of the bridge circuit for operation of strain-gage pressure transducers is the desire for a zero signal output for zero pressure input. Practical considerations prevent obtaining a bridge that is exactly balanced in the rest condition. There is not only the normal gage to gage resistance tolerance, but the mounting process itself can introduce initial strains that are unequal in the various gages. There are also residual signal outputs resulting from ambient pressure which are different from the original zero or pressure to which the transducer was exposed during manufacture (i. e., tare loads are applied to the transducer). A balance network is used to null these residual signal outputs.

Figure 57 shows the most common circuit for balancing the simple bridge. This circuit modifies the voltage on one side of the bridge by shunting the bridge elements so that the voltage at the midpoint is equal to the voltage at the midpoint of the opposite side. To minimize the loading effect on the active arms that are being shunted while retaining adequate balance resolution, fixed resistors can be added. A single limiting resistor is connected in series with the potentiometer wiper.

In designing balance networks, the variables of resolution and range must be considered. The resolution of the balance network is a function of the number of turns of the balance potentiometer and the type of potentiometer winding (i. e., wire wound, film, etc). For most applications, the range of the balance network may be accurately approximated by

$$\frac{e_o}{V} = \pm\frac{R}{4R_4}\ (\text{if } R_4 >> R) \tag{15}$$

Shunt balance networks also have the effect of reducing the sensitivity of the bridge. This loading effect results from the balance network desensitizing the side of the bridge which it shunts. Thus, the $\Delta R/R$ obtained from this side of the bridge is less than without the balance network. When ΔR is small relative to $R_5 + R$, the shunting effect is defined by

$$\left(\frac{\Delta R}{R}\right)' = \frac{\Delta R}{R}\left(\frac{R_5}{R_5 + R}\right) \tag{16}$$

where R_5 is the effective shunt created by the balance network across the active bridge arm. R_5 is expressed mathematically as follows:

$$R_5 = \frac{R_1R_2 + R_2R_4 + R_4R_1}{R_2} \text{ or } \frac{R_1R_2 + R_2R_4 + R_4R_1}{R_1}$$

depending on which bridge arm is considered. When $R_1 = R_2$, $R_5 = R_2 + 2R_4$ or $R_1 + 2R_4$.

$\frac{\Delta R}{R}$ = unshunted unit resistance change of the bridge

$\left(\frac{\Delta R}{R}\right)'$ = shunted unit resistance change of the bridge

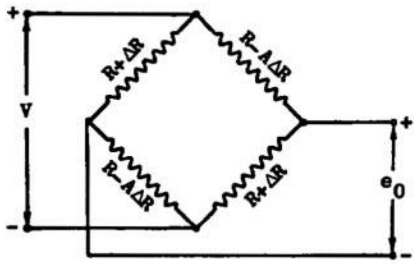


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Fig. 55 Full Bridge Transducer

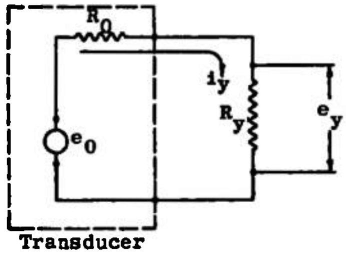

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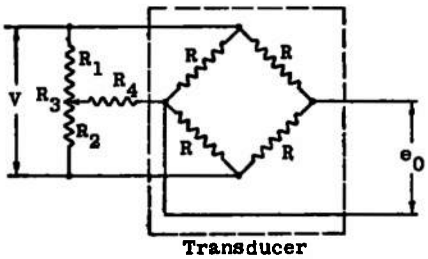
Fig. 56 Closed Output Circuit



Where: R_1 = top portion of potentiometer,
R_2 = bottom portion of potentiometer,
R_3 = total potentiometer resistance,
and R_4 = wiper resistor.

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Fig. 57 Parallel Balance Network

For a fully active transducer with the balance potentiometer centered, the relative output is

$$A = \frac{R_5 + 0.5\ R}{R_5 + R} \tag{17}$$

where

A = output relative to the output without the balance network

The attenuation of the transducer output attributable to the shunting effect of the balance network is

$$B = 1 - A = \frac{1}{2}\left(\frac{R}{R + R_5}\right) \tag{18}$$

where

B = decrease in output from the output without the balance network

To minimize this loading effect, the resistance of the balance network should be made as high as possible. This will also decrease the current drawn through the balance network. For maximum accuracy, the transducer should be calibrated with the same type balance network used in the actual measuring system.

Voltage bucking balance networks are shown in Figs. 58 and 59. This type of balance network adds a series balancing voltage e_2 to the transducer zero output voltage e_1 to produce the net output voltage e_o of the circuit (119):

$$e_o = e_1 + e_2 \tag{19}$$

By varying the balance network potentiometer, e_2 can be made equal in magnitude and opposite in polarity to e_1, producing a balanced condition of zero output.

The balance network of Fig. 58 uses the same excitation source as the transducer. This network produces a loading effect on the transducer output as in the case of the shunt balance network of Fig. 57. The loading effect and balance range can be essentially independent of each other.

The balance network of Fig. 59 is similar in principle to that shown in Fig. 58, but requires a separate excitation voltage source. This network does not produce a loading effect on the transducer output. However, the balance is dependent on the stability of the two separate power supplies. For the shunt balance network of Fig. 57 and the voltage bucking network of Fig. 58, the balance is not affected on a first order basis by the voltage stability. It may, however, have second order effects caused by internal heating and related effects. The balance network is a full-bridge, half active, with fixed resistors, R_7, in the excitation leads (120). In the network shown, all four bridge resistors are equal in value when the potentiometer is in the center position.

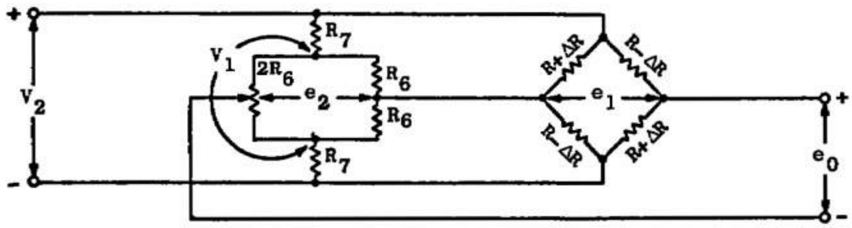

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Fig. 58 Voltage-Bucking Balance Network

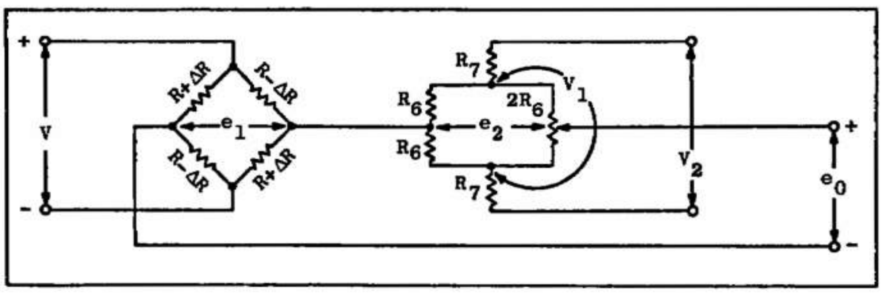

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Fig. 59 Voltage-Bucking Balance Network

For the circuit shown in Fig. 59 (and to a good approximation for Fig. 58),

$$\frac{e_2}{V_1} = \pm\frac{\Delta R_6}{2R_6} \tag{20}$$

where V_1 is the voltage across the balance network bridge input terminals. With respect to the excitation voltage (V_2), the output of the balance network is:

$$\frac{e_2}{V_2} = \pm\frac{\Delta R_6}{2(2R_7 + R_6)} \tag{21}$$

The maximum balance range is obtained when ΔR_6 is maximum, which is R_6 in the circuit shown:

$$\frac{e_2}{V_2}(\text{max}) = \pm\frac{R_6}{2(2R_7 + R_6)} \tag{22}$$

It can be seen that the balance range is independent of the resistance of the transducer, R However, the balance network does increase the effective output resistance of the transducer. The output resistance of the circuits of Figs. 58 and 59 is:

$$R_o = R + R_6\left[1 - \left(\frac{\Delta R_6}{2R_6}\right)^2\right] \tag{23}$$

With the balance potentiometer in the center position ($\Delta R_6 = 0$), the increase in output resistance is R_6. This increase in resistance changes to $3R_6/4$ as ΔR_6 increases to its maximum value of R_6. The output resistance is, therefore, a function of initial transducer balance. This factor may be of significance if the transducer is used in a low impedance circuit such as a galvanometer.

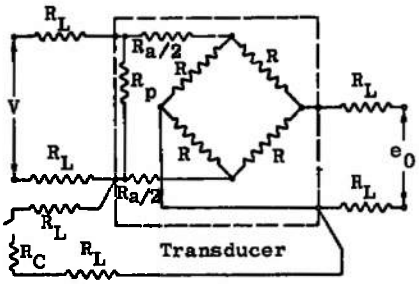
3.2.1.3 Shunt Calibration

A common method used to provide an electrical calibration of a strain-gage pressure transducer system is to shunt a resistor across one arm of the transducer. This technique produces an output which simulates applying a pressure to the transducer. The relationship between the calibration resistor and the pressure is previously determined in a laboratory calibration. This is accomplished by applying pressure to the transducer to determine its output versus pressure curve. With the pressure removed, the shunt resistor is then applied and the output is read. The simulated pressure is determined by correlating this output with the output versus pressure data (121).

Single shunt calibration is shown in Fig. 60. Application of the shunt resistor, R_c, decreases the resistance of the leg shunted, producing a negative ΔR. This unbalances the bridge, simulating a pressure applied to the transducer. With no line resistance, all R_L's equal zero, the output produced by R_c is defined by

$$\frac{e_o}{V} = \frac{R}{4\left[R_c + 0.5\left(R - 0.5\,R_a\right)\right]} \tag{24}$$

Certain factors not readily apparent from Eq. (24) affect the accuracy obtainable with the use of shunt calibration in the field. The major factors are transmission line resistance, parallel zero balance network, and temperature effect. In a four-wire system, line resistance produces an error in the shunt-to-load correlation. These errors are defined in (121). The use of a six-wire system as shown in Fig. 60 virtually eliminates the transmission line resistance error, thereby retaining the shunt-to-load correlation essentially independent of line resistance. Thus, for most applications using the six-wire system, this error can be ignored.



Where: R_C - external shunt calibration resistor,
R_a - transducer input circuit resistors,
R_p - transducer input pad resistor,
R_L - transmission line resistance.

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Fig. 60 Single Shunt Calibration

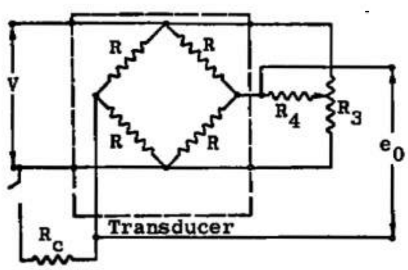

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Fig. 61 Shunt Calibration with Parallel Balance Network

The use of shunt calibration with a parallel balance network is shown in Fig. 61. The balance network is on the opposite side of the bridge from the calibration resistor. It has negligible effect on the output because of the calibration resistor. However, the balance network does decrease the output resulting from applied pressure. Therefore, the shunt-to-pressure correlation is affected by the presence of the balance network. If this error is not tolerable in the measuring system, it can be avoided by determining the shunt-to-pressure correlation with the balance network in the system. The use of a balance network on the same side of the bridge as the calibration resistor will cause an error which varies with the position of the wiper of the balance potentiometer (i. e., initial unbalance of the transducer). This error is not controllable and cannot easily be calibrated out as in the previous case. Therefore, the shunt resistor should be used on the opposite side of the bridge from the balance network.

The output attributable to pressure and the output attributable to shunt calibration may have thermal coefficients which differ. Thus, the shunt-to-pressure correlation may vary from the initially established room temperature value. When shunt calibration is used over a temperature interval, the shunt-to-pressure correlation should be established by calibration over that temperature interval.

Double-shunt calibration is essentially the same as the single-shunt technique (Fig. 60) with the addition of a second shunt resistance, R_c, across the diagonally opposite leg of the bridge. Double-shunt

calibration is also expressed by Eq. (24), except that the output will be doubled. The transmission line resistance error deserves the same consideration, but it requires an eight-wire system to eliminate the error. Double-shunt calibration is less sensitive to parallel balance networks than single-shunt calibration. This results from the fact that the balance network reduces the output caused by pressure and the output caused by one of the calibration resistors by approximately the same amount. However, the error remaining is a function of the position of the balance potentiometer and represents an uncontrolled error as discussed above. Consequently, parallel balance networks are not recommended for use with general purpose double-shunt systems. They may be used if the error is within the system tolerances or if a calibration is performed with the balance potentiometer in the position required for system balance.

3.2.1.4 Power Supply Considerations

In the typical schematic representation of the strain-gage bridge circuit, it is common to show the power supply isolated from all other circuit commons and the AC power line. It is a fairly common practice, however, to employ a single voltage regulated power supply with a fairly high current capacity to excite a large number of independent bridges. This saves a good portion of the cost involved in exciting the bridges, since one large capacity power supply is cheaper than a number of individual supplies having a relatively low current capacity (117).

There are several considerations that should be carefully weighed before making the decision to use a common power supply. The most important considerations are the problems of isolation and shielding. Power supplies are available that offer very low coupling to the shield environment and to power or earth ground. As a matter of fact, they come very close to approximating the ideal battery as a source. If a second bridge circuit is connected to the supply, however, this isolation has been compromised, and any local anomalies or stray coupling in any one transducer immediately become common to all. It is generally necessary to establish one side of the supply as system ground in order to keep system noise under control. Shielding for noise rejection becomes more difficult in the common power supply case.

The isolation problem is even more significant. Looking at Fig. 62, which shows a pair of bridges connected to a common supply, it is obvious that the signal leads cannot be made common or bridge halves will be paralleled. This results in cross coupling of data between channels in addition to decreasing the output of each bridge. The decision to use common power, then, dictates that both sides of each bridge be isolated at the output. In all probability, single-ended amplifiers cannot be used even if they are isolated and single ended, because the single ended amplifier will likely have its input and output grounds in common. Thus, the low sides are coupled through the amplifiers to the readout or recorder, which will bring the low side inputs to a common point. This means that differential input amplifiers must be used. Looking at the cost of differential amplifiers shows that there is little, if any, overall system cost savings realized by a common power supply.

The most frequently encountered use of common power supply systems is the case where the individual outputs are routed to a low level, time sharing multiplexer (Section 3.2.6). Differential inputs are normally used (at least both sides are switched as well as the shield), and the bridge outputs are left open before and after their dwell on line. Since only one bridge is connected to a load at a time, they never can become common.

Another problem arises in attempting to standardize the individual outputs. With individual power supplies, the voltage applied to each bridge can be set so that the outputs of all bridges are some standard level and can be interpreted directly in terms of engineering units. With a common power supply, the only way to control the excitation to individual bridges is to install a variable resistor in series with the excitation to the bridge. This seriously degrades the load regulation of the power supply as seen by the bridge. If the bridges are used in an environment subject to large temperature changes, and thus large resistance changes in the series resistors, then this is a bad circuit to use.

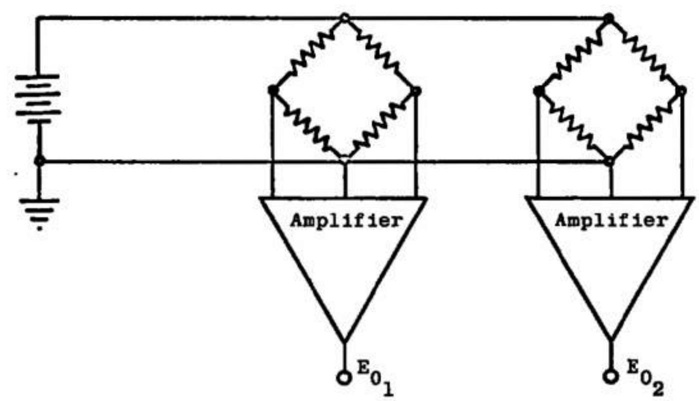

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Fig. 62 Common Power Supply Connection

In addition, the ability to remotely sense the supply so that the voltage is held constant at the bridge rather than at the supply is lost. If the individual bridges are located very far from the power supply, a patch panel can be installed near the bridges and the sense leads connected at that point. The voltage drop in the power buss is then negated, but not in the individual bridge leads.

Technically, there are few valid arguments for going to common power supplies, but economically, common power supplies can offer some strong arguments in certain specialized installations.

Another power supply consideration is the question of whether to use constant voltage or constant current supplies. In general, constant current is preferred for transducers utilizing semiconductor strain-gage sensors. The reasons for this are given in the following section.

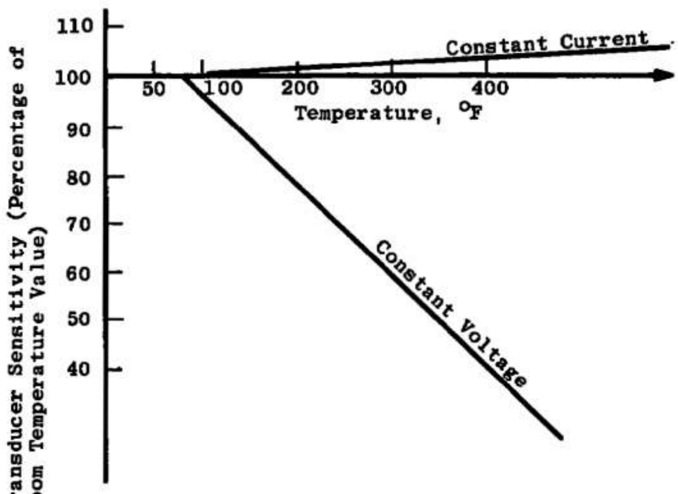
3.2.1.5 Signal Conditioning for Semiconductor Strain-Gage Transducers

Semiconductor strain gages have certain characteristics, notably their high gage factor, which make them very attractive for use in pressure transducers. However, these advantages are accompanied by some features which require signal conditioning circuitry quite different from that employed for conventional metal foil or wire strain-gaged transducers.

The semiconductor gages typically have a very high positive thermal coefficient of resistivity compared to wire or foil gages. The bridge resistance is also likely to vary over a considerably wider range than the resistance of an equivalent metal gage bridge. In semiconductor gages, $\Delta R/\epsilon$ (ϵ = unit strain) is constant with temperature; therefore, the gage factor ($\Delta R/R\epsilon$) decreases significantly with increasing temperature. This dependence of strain sensitivity on bridge resistance change versus temperature can be eliminated by supplying a constant current excitation to the bridge. The constant current will cause the applied voltage to the bridge to vary in direct proportion to bridge resistance. Thus, as the gage factor decreases, excitation increases because of the natural positive temperature coefficient of the gage. The result is virtually constant sensitivity with changing temperature (Fig. 63) (122).

Another factor which can affect signal conditioning choices is the considerably higher ΔR that the semiconductor gages exhibit. This can result in bridge-induced nonlinearities being much more significant, especially when less than four-active-arm bridges are used. It also suggests that constant current excitation might be more desirable than constant voltage as a means of reducing this nonlinearity.

When pressure transducers that employ semiconductor gages are bought, the odds are they will incorporate impedance compensating networks inside the transducer housing. What appears to be a simple four-arm bridge when looked at from the output connector, could very well be 8, 10, or 12 elements connected to optimize the thermal behavior of the transducer. Transducers are designed to be employed with either constant current or constant voltage, and it is imperative that the proper excitation source be used.



(Figure Reproduced through Courtesy of Baldwin-Lima-Hamilton Corp.)

Fig. 63 Transducer Sensitivity vs Temperature for Semiconductor Strain Gages with Constant Current and Constant Voltage Excitation

3.2.1.6 Potentiometric Transducer Signal Conditioning

Although strain-gage pressure transducers are certainly the most common of the variable resistance type, quite a few of the potentiometric type are used. Signal conditioning equipment for potentiometric transducers is essentially the same as that for strain-gage bridges except that it must accommodate very high resistance changes in the active legs and can tolerate little or no output loading (117).

Potentiometers are generally built as accurate voltage dividers and not as accurate variable resistors. Typically, a potentiometer is linear to within 0.2 percent or better as a voltage divider but has a total resistance tolerance of 5 percent or so and might have a resistance temperature coefficient that results in a change in resistance of several percent over its rated temperature range. To the extent possible then, the potentiometers should be operated only as voltage dividers.

The usual bridge completion for a potentiometer is another potentiometer. The balance pot in the signal conditioner can be used for this function without any extra components (Fig. 64). With a potentiometric transducer, there is relatively little confidence in the initial position of the potentiometer wiper during calibration. The system calibration scheme should therefore be a substitution method rather

than a shunt or insertion methoo. Either resistance substitution or voltage substitution can be used at the convenience of the instrumentation engineer.

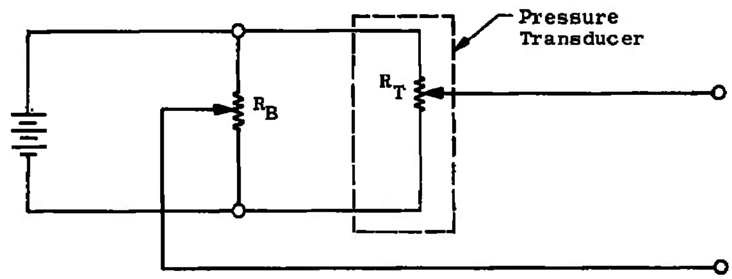


Fig. 64 Potentiometer Signal Conditioning

3.2.2 Signal Conditioning for Variable Reluctance and Linear Variable Differential Transformer Pressure Transducers

The two transducer types covered by this section differ somewhat in the generation of their output signals, but the resulting signals and the signal conditioning they require is sufficiently similar to warrant a common treatment. Figure 65 shows a schematic representation of the two types.

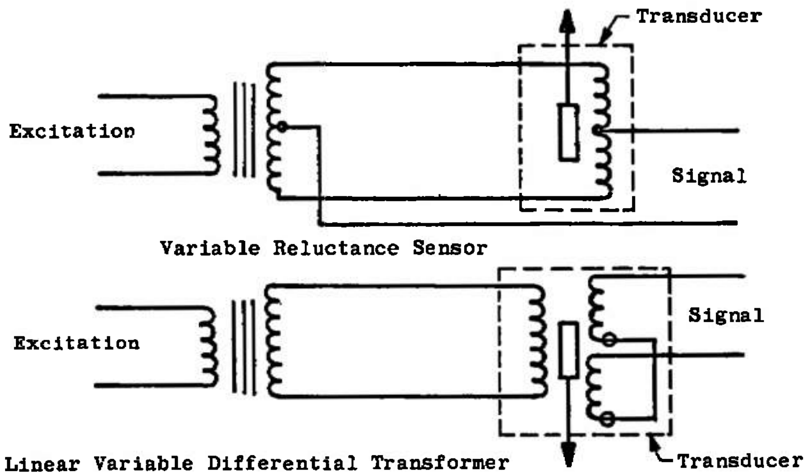


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Fig. 65 Linear Variable Differential Transformer and Variable Reluctance Sensor

Like the transducers of the previous section, variable reluctance and differential transformer pressure transducers are passive devices. That is, they depend upon an externally supplied excitation source to provide an output signal. Unlike their resistive counterparts, however, these sensors rely on variation of their reactive properties as a transduction principle and consequently will operate only from an AC voltage (or current). Their conditioning systems are very much like the AC systems used for strain gages (117). A block diagram of a typical carrier amplifier-demodulation system which is generally used for conditioning variable reluctance and differential transformer pressure transducers is shown in Fig. 66. The amplifier operation is as follows: The transducer is excited with a regulated AC voltage which is in turn amplitude modulated by the transducing device. The balancing network is used to null resistive and reactive components of the transducer unbalance. The resistive component also provides a convenient means of adjusting the amplifier zero. A bandpass filter removes unwanted noise and harmonic signals and passes only the carrier and its sidebands. The transducer signal is amplified by the AC amplifier, synchronously demodulated, and filtered. In Fig. 66 typical signals are shown at various points in the amplifier for an input from a pressure transducer. Several components of the system can be omitted. For example, if the transducer signal is of sufficient magnitude, then the AC amplifier is not needed. Or, if the transducer is initially balanced, then the zeroing networks can be eliminated. Also, non-synchronous detection (simple rectification) can be employed if bipolar signals are not to be conditioned and if linearity, noise, and frequency response are not of prime importance. Nonsynchronous demodulation rectifies any signal coming into it, regardless of frequency or phase relationship to the carrier. Therefore, the demodulator output does not indicate a difference in a positive or negative pressure. Also, noise signals are not rejected but are demodulated along with the

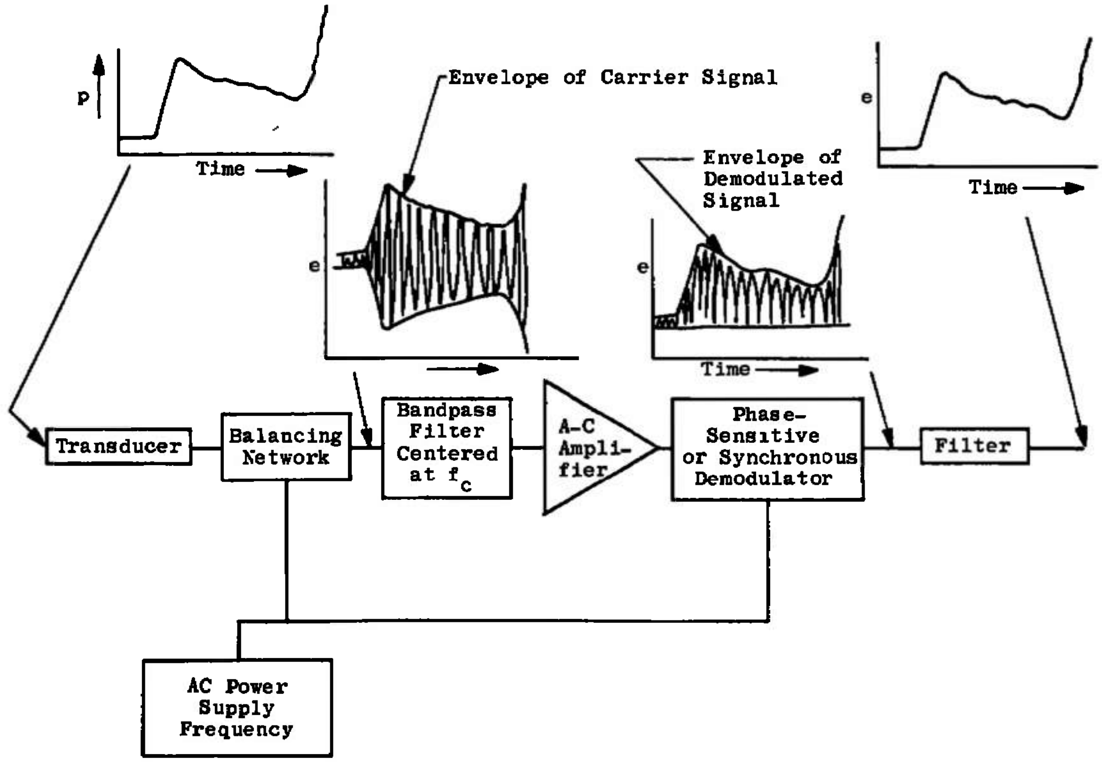


Fig. 66 Carrier Amplifier

transducer signal. A synchronous demodulator, on the other hand, is not controlled by the incoming signal but by a reference signal which is synchronized with the carrier. Thus, when the pressure reverses on a transducer and its signal phase shifts by 180 deg, the demodulator output also reverses. Noise signals reaching the demodulator are passed, partially rejected, or completely rejected, depending on their phase relative to the reference signal. Figure 67 illustrates the function of both types of demodulators. Because the signals from VR and LVDT transducers are not generally in phase or 180 deg out of phase with the carrier, the carrier reference signal to the synchronous demodulation must be adjustable.

Variable reluctance transducers are usually three-terminal devices and are essentially the magnetic equivalent of a two-active-element resistance bridge. The impedance of the two reactive elements will vary in a complementary manner as in the case of the two-arm strain-gage bridge. Therefore, the most convenient method of operating the variable reluctance sensor is in a bridge circuit. Since excitation of the bridge will always be from an AC source, an additional simplification is possible. The reference portion of the bridge can actually be the driving transformer using center tap as the reference midpoint.

Differential transformer devices are essentially what their name implies. They are constructed as a loosely coupled transformer having one primary and two secondary windings. A mechanical input to the device causes changes in the magnetic coupling to the individual secondary windings. These changes are essentially complementary in nature so that an increase in the output voltage of one secondary is accompanied by a corresponding decrease in the other. The secondary windings are connected in series opposition so that the outputs tend to cancel for a symmetric flux distribution (usually midrange of the mechanical input). The output voltage on either side of this null point should be a linear function of the magnitude of mechanical input and will shift its phase relative to the input by 180 deg as it goes through null.

This characteristic of 180-deg phase change about null is what provides a center zero data output. Ideally, the output would be exactly in phase or exactly 180 deg out of phase with the excitation. However, such is not the case. Transducers of either type will be found to have some excitation frequency at which they will exhibit essentially zero phase shift of the carrier. For excitation frequencies above or below this zero phase frequency, the output signal will either lead or lag the excitation by an amount that is a function of how far from its optimum frequency it is being operated.

Normally, transducers have been designed to optimize at the carrier frequency used. Other selection criteria can occasionally dictate a transducer that will have a rather high carrier phase shift at the frequency being used, and the signal conditioner will then have to accommodate this added factor. The general assumptions on relative frequency response that were made when discussing AC excitation of

strain gages apply equally well here. However, it may be slightly more difficult to reach an information bandwidth of one fifth of carrier frequency because of the higher demodulator noise. These magnetic devices have a tendency to be harmonic generators which contribute to noise in the output signal.

When it is impractical, because of transducer selection criteria or for information frequency response considerations, to operate the transducer near its optimum frequency, it will be necessary to alter that phase shift in the carrier amplifier. It is not practical to shift the phase of the modulated carrier by passive electronic mesns since such circuits do not shift the phase of all frequencies in the range of interest by the same amount, and a circuit-induced distortion will result. The reference signal, on the other hand, may be easily shifted since no frequency components except the carrier exist.

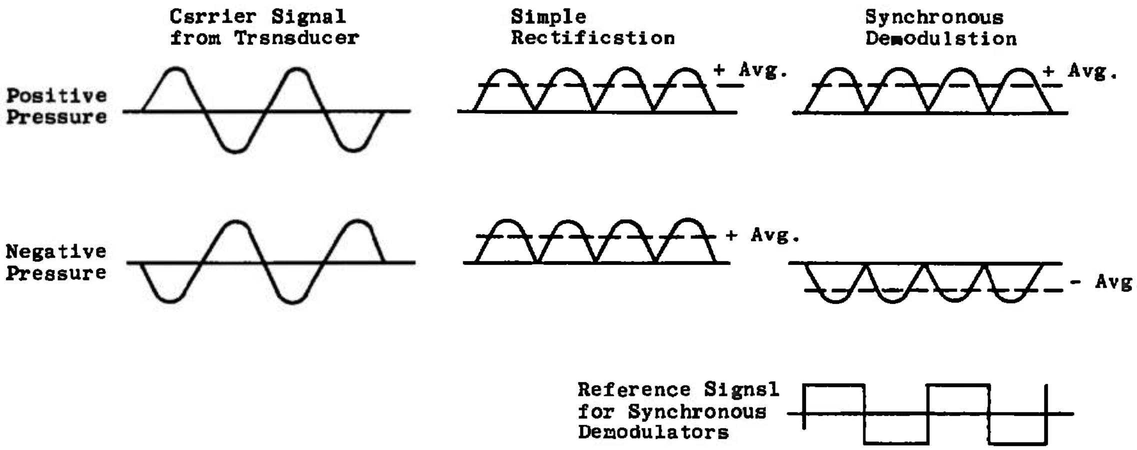


Fig. 67 Operation of Simple Rectifier and Synchronous Demodulators

The phase shift characteristics of variable reluctance and differential transformer devices are, unfortunately, not a simple matter of carrier frequency. They will be found to vary as a function of input parameter as well, so that reference phase correction must be optimized over the input range. The inevitable result is that the phase shift will be something other than zero near null. Since output zero will result from a balanced condition of the in-phase component, a small amount of signal that is either 90-deg leading or 90-deg lagging the reference will be present. This residual signal (quadrature voltage) will degrade the signal-to-noise ratio near null if left alone. The standard practice is to use the balancing circuitry to inject a quadrature component at the input of the carrier amplifier that is equal in magnitude and opposite in phase to the quadrature component present in the transducer output signal.

As previously mentioned, under certain conditions, nonsynchronous systems work quite well with these types of trsnsducers and are considerably less complicated. The simplest such technique utilizes a six-wire differential transformer with the secondary windings brought out separately. The secondary outputs are separately rectified and then summed at DC. Naturally all components of a secondary output (whether noise or information) are considered signsl so that the noise rejection with this system is essentially nil.

The most convenient source of AC for the carrier is the 60-Hz power line. A common filament transformer will suffice to drop the 115-volt line down to an acceptable level for exciting the transducer. Operation in this manner should be limited to constant temperature use of the transducers, however, since the temperature coefficient of sensitivity will greatly suffer. The input inductance of the typical differential transformer will be very low at 60 Hz, with the result that input current will depend almost entirely on the DC resistance of the input. This can be compensated by exciting the unit from a constant current source (or at least a very high resistance source) so that primary resistance changes are effectively swamped out. This, however, will not completely compensate for the temperature variation in the output. The primsry to secondary coupling of the device will be quite high. With any practical load (especially true with the individually rectified outputs), the net output under load will be highly temperature dependent.

3.2.3 Signal Conditioning for Piezoelectric Transducers

Pressure transducers based upon the principle of piezoelectricity offer many important advantages for dynamic testing. They require no outside source of excitation, they remove relatively little energy from the system they are measuring, they are generally quite small and light weight, have excellent high frequency response, and have an unusually wide dynamic range. However, many of these advantages become problems in the signal conditioning (117).

Since they are self-generating devices, with a low mechanical energy advantage, very little electrical energy is available to the signal conditioner. Another way of saying this is that the transducer presents a very high source impedance to the conditioner, and further, it will be essentially purely capacitive. The phase and amplitude characteristics will then be a direct function of the load on the device.

Their excellent high frequency response does not come without compromise either. The frequency response characteristic is generally one of an undamped, single-degree-of-freedom system with a resonance somewhere in the range from 30 to 150 kHz. A broadband amplifier is required to utilize high frequency response, and additionally, the amplifier response characteristics should reject signals at the transducer natural frequency. The wide dynamic range requires that electrical noise be kept to an absolute minimum, in a system which is already noise prone.

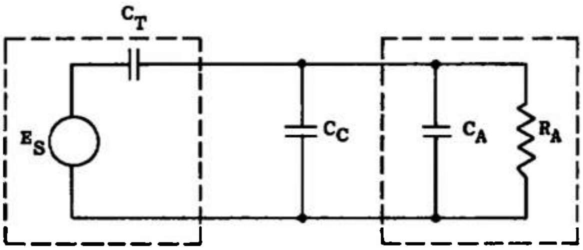
There are two basic techniques being employed today to condition piezoelectric transducer outputs. These are

1) high impedance voltage amplifiers
2) charge amplifiers

A third category (remote electronics) is sufficiently different in practice to warrant separate treatment, although in theory it is simply a matter of locating the amplifier in or adjacent to the transducer.

In utilizing voltage amplifiers for conditioning piezoelectric transducer outputs, the amplifier input impedance must be very high compared with the source impedance to minimize the effect of the amplifier on the phase and amplitude characteristics of the system. This is entirely practical for an amplifier using input devices such as electrometers and insulated gate, field-effect transistors. But, because of the reactive nature of the source, an equally significant portion of the load is the interconnecting cable itself.

Figure 68 shows the equivalent circuit of a typical piezoelectric transducer with output amplifier. The voltage source E_s and capacitance C_T represent the transducer, and the cable has been represented by a single shunt capacitor C_C. (This is a satisfactory representation for the low frequency, short length case, but a closer approximation of the actual transmission line is necessary for high frequencies or long lines.) The amplifier input is represented by a parallel capacitor (C_A) and resistance (R_A).



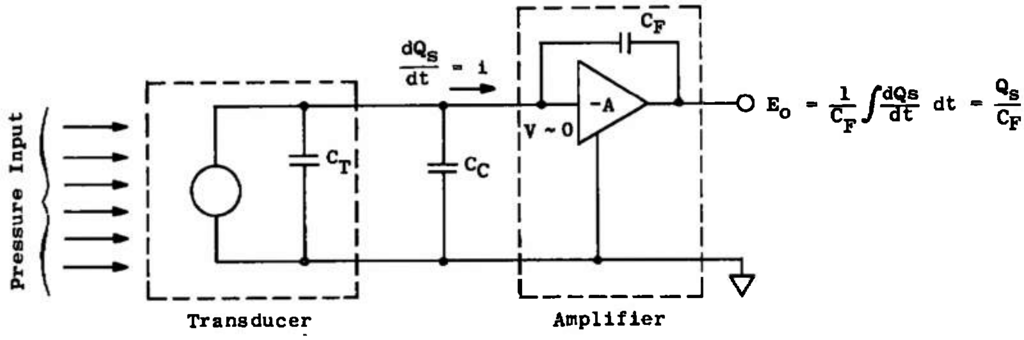
(Figure Reproduced through Courtesy of ENDEVCO, Inc.)

Fig. 68 Voltage Amplifier Equivalent

Typical values of transducer capacitance can be as low as 300 pF. The coaxial cable used for the interconnection will be on the order of 30 pF/ft. It obviously does not take much cable to substantially lower the available voltage, even if an ideal amplifier input is assumed ($C_A = 0$, $R_A = \infty$).

A second factor that must be considered in using voltage amplifiers for piezoelectric devices is the system low frequency response that will result in any given installation. From a basic knowledge of the signal generating mechanism of a piezoelectric transducer, it must be conceded that steady-state response cannot be obtained with a practical voltage amplifier. The actual low frequency cutoff may not be so readily apparent, however. Referring back to Fig. 68, it can be seen that the amplifier input resistance in combination with the total shunt capacitance forms a high pass, first order filter with a time constant $\tau = R_A(C_T + C_C + C_A)$. Substituting typical values for the circuit constants ($R_A = 1000\ M\Omega$, $C_T = 300$ pF, $C_C = 300$ pF, and $C_A = 20$ pF), we find that the response in this instance would be down 3 db at approximately 0.25 Hz. For lower source capacitances (less cable or very low capacitance transducers) or lower amplifier input resistances, this frequency can approach data frequencies and become a matter of some concern.

In recent years, the trend has been away from voltage amplifiers and more toward the so called "charge amplifiers" in order to avoid the cable capacitance effects on system gain and frequency response. A charge amplifier is essentially an operational amplifier with capacitive feedback. The transducer is connected to the summing junction. A simplified representation is shown in Fig. 69. Because of the



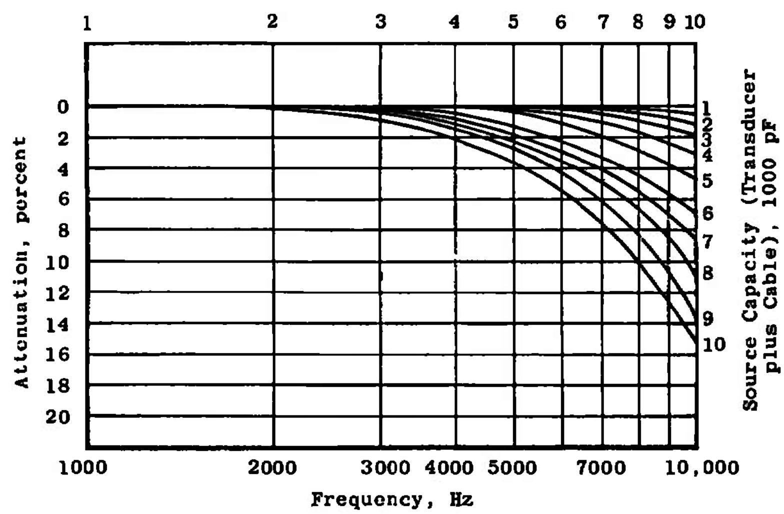
(Figure Reproduced through Courtesy of ENDEVCO, Inc.)

Fig. 69 Charge Amplifier

nature of the operational amplifier with feedback, the amplifier input is maintained at approximately zero voltage. Thus, the charge produced by a pressure input is immediately drained off. Since the amplifier input impedance is effectively infinite, all the charge initially on the transducer is transferred to the feedback capacitor.

$$E_o = \frac{1}{C_F}\int i\,dt = \frac{\ }{C_F}\int\frac{dQ_s}{dt} = dt\,\frac{Q_s}{C_F} \qquad (25)$$

This shows that the amplifier output, E_o, is independent of the transducer and cable capacitance. In practice, however, cable length is a consideration at high frequencies as shown in Fig. 70.



(This Figure Was Adapted from "Model 2620 Amplifier Data Sheet," ENDEVCO, Corp., Pasadena, Calif.)

Fig. 70 Effect of Source Capacitance on High Frequency Response for a Typical Charge Amplifier

With either the high impedance voltage amplifier or the charge amplifier, the most important function of the signal conditioning system is accomplished, that is, to satisfy the interface demands of the transducer. The additional functions of ranging and standardizing can be provided with relative ease by gain changes in the amplifiers, giving a greatly extended dynamic range capability.

There is also a rather high probability that filtering of the resultant signal will have to be provided on both the low and high ends of the information band. Piezoelectric devices are often prone to exhibit high sensitivity to thermal transients. This characteristic, referred to as a pyroelectric effect, generally exists only at very low frequencies (or as transients with long time constants) so that it is possible to get a rather high order of rejection without affecting information through the use of high pass filters just below the minimum required frequency response. As noted earlier, voltage amplifiers with moderate to low input impedances already exhibit this characteristic. It is only necessary to be able to

control the cutoff point to put it to good use. In a charge amplifier, the addition of a resistor in parallel with the feedback capacitor will have the effect of decreasing closed-loop gain at low frequencies.

For general broadband noise rejection above the maximum data frequency, low pass filters on the amplifier output are generally satisfactory. Occasionally with charge amplifiers, however, high amplitude, short duration input transients will overload the amplifier and obscure valuable data during recovery. It is then desirable to filter before the amplifier input. One way that this can be accomplished is by adding series resistance at the amplifier input. The resulting high frequency breakpoint will be at $f = \frac{1}{2\pi RC}$, where R is the series resistance and C is the total source capacitance.

With systems involving very high input capacitances (usually a result of very long lines), neither the voltage amplifier nor the charge amplifier offers a very satisfactory solution to the conditioning problem. The signal-to-noise ratio suffers with the voltage amplifier because of decreased available signal attributable to capacitive loading. In a charge amplifier, effective input noise is a direct function of input capacitance, and although the available signal is independent of capacitance, the signal-to-noise ratio suffers because of the increased noise level. The obvious answer is to move the signal conditioning to the other end of the line. Since this is not always possible, a reasonable compromise would seem to be to move part of the conditioning to the remote point.

There have recently been introduced a number of systems that employ amplifiers (either charge or voltage) that are inserted in the normal data leads close to the transducer. Transducer manufacturers are also providing piezoelectric devices with the unloading amplifier as an integral part of the transducer housing (74). Other than the obvious considerations of the operating environment, this appears to offer a satisfactory solution to the accommodation of long data lines. A typical such system is shown in Fig. 71.

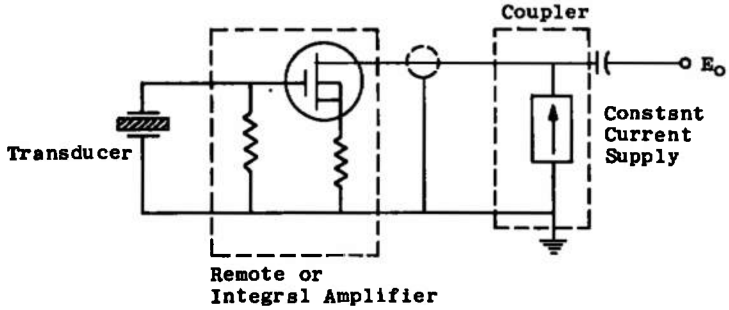


Fig. 71 Line Driver Circuit

Two practical problems exist from a circuit standpoint, however, that may be of concern to the instrumentation engineer. The first is the decreased dynamic range capability of such a system since input amplifier gain can no longer be changed in order to accomplish range change. The second is a restricted high frequency response signal amplitude capability because of the limited current capability of the remote amplifier. By the time these two limitations have been overcome, 90 percent of what would constitute the signal conditioning equipment is at the remote location, and it would be just as well to put the amplifier there.

3.2.4 Signal Conditioning for Variable Capacitance Transducers

Variable capacitance pressure transducers, though not used as extensively as strain-gage, piezoelectric, or reluctance-type transducers, still find a wide variety of applications that are important in wind tunnel pressure measurements. Their diversity is shown by the fact that they can be used for extremely low, semi-static pressure measurements (56, 123, 124, 125, and 126), for rapid response measurements in shock tubes (70 and 127), or in free-flight telemetry applications (60, 61, and 128). This diversity of application requires a similar diversity of signal conditioning instrumentation. In general, the capacitance transducers which are commercially available are designed to operate with a particular type of signal conditioning equipment, and ordinarily the transducer and adjunct instrumentation are purchased as a unit and neither works well with other equipment.

The variable capacitance transducer is, of course, a passive device and must have excitation provided. For high accuracy, an AC bridge may be employed in either a balanced or unbalanced mode. Manual balance or servo balance may be chosen if a balanced bridge scheme is employed. Figure 72 shows a manually balanced bridge circuit; the additional features required to convert this circuit to a servo type are obvious. Excitation voltages as high as 200 volts at frequencies ranging from 400 Hz to 2.5 kHz are common with this circuit. Accuracies of 0.05 percent of full scale are typical and pressures as low as 2×10^{-7} psi may be resolved with a 1-psi transducer (129).

When the pressure sensor is used in an unbalanced bridge circuit, it does not include a servo loop and, therefore, is able to provide more rapid response, smaller size and weight, and greater output. It can be used in conjunction with the normal strain-gage carrier amplifier systems; typical output sensitivity is 0.25 volt per volt at maximum pressure.

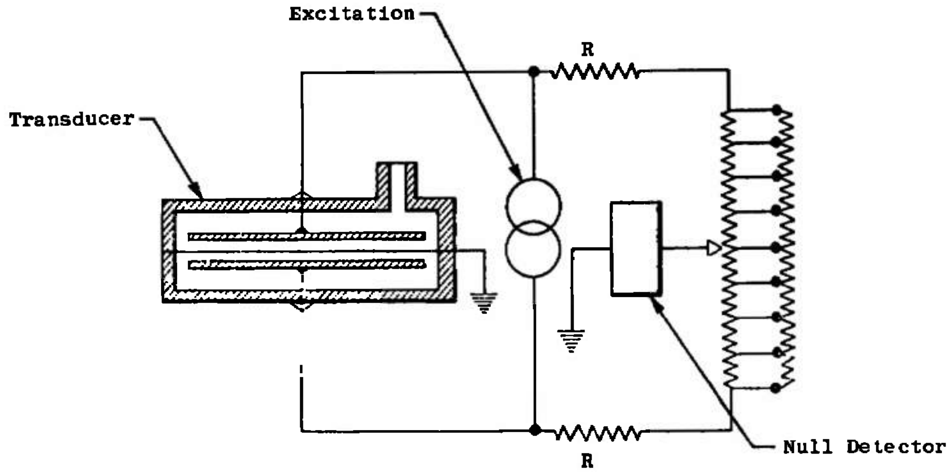


Fig. 72 Variable Capacitance Pressure Transducer in Bridge Circuit

For rapid response measurements (on the order of 15 μ sec), circuitry may be employed which utilizes the capacitance of the transducer along with an inductance which is contained in the pressure transducer to form a tuned radio frequency circuit (130). This circuit is link coupled by means of a low impedance cable to an oscillator-detector which consists of an RF oscillator coupled to a diode detector circuit. The small changes of transducer capacitance produce relatively large impedance changes in the diode detector circuit, and the detector circuit's output is proportional to the pressure applied to the transducer. The detector output is coupled through a cathode follower and filter network to provide a low impedance DC output signal.

Wind tunnel measurements which require telemetering of data from a "free-flying" model generally employ variable capacitance transducers because of their compatibility with simple transmitting circuits (60, 61, and 128) which utilize the transducer along with an inductor to form a tank circuit as shown in Fig. 73. The reception system employs commercial high frequency receivers which provide an output voltage proportional to frequency deviation. A block diagram of a complete measuring system is shown in Fig. 74. Pressures as low as 0.0005 psid have been measured using these techniques.

Other signal-conditioning techniques which have found limited usage are polarization techniques (5 and 70) and the use of a three-terminal parallel-T circuit (127). Both of these techniques are primarily for short duration, rapid response measurements.

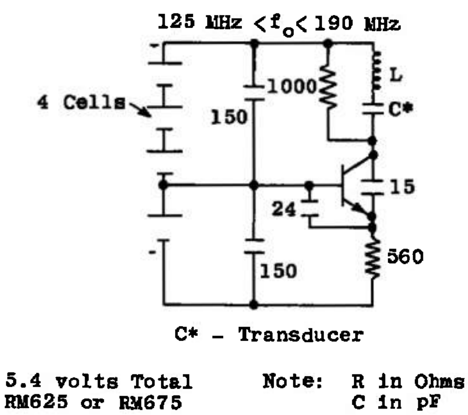


Fig. 73 Clapp Oscillator

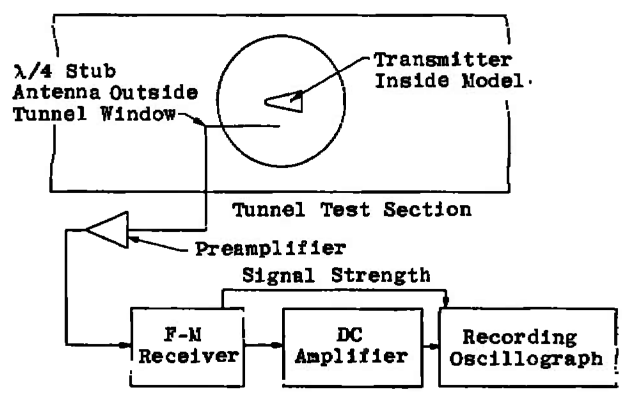


Fig. 74 Single-Channel Telemetry System

3.2.5 Compensation for Acceleration Effects

Transducers employed for pressure measurements in wind tunnel environments are often subject to vibrations which accrue as a result of various tunnel operations. At times data recording can be delayed until the vibrations have damped to a level sufficiently low not to affect the transducers, but in many instances sufficient test time is not available or the source of vibration is continuous. In such cases, the accuracy of the measurements can be degraded beyond tolerable limits unless some corrective measure is taken. One such method is to use an electronic filter whose bandpass covers the range of interest from a data standpoint but which rejects or attenuates satisfactorily in the frequency region of the troublesome vibrations. Another remedy for troubles of this type is to use transducers which can be shock mounted (Section 3. 1. 1) (isolated from the vibration) or which are provided with internal compensation for acceleration (Section 2) (51 and 74). When neither of the aforementioned is feasible, compensation of vibratory effects may be provided by mounting an accelerometer in such a way as to sense the vibration and then electrically summing the signal from the accelerometer and the pressure transducer. When properly summed, the acceleration signal produced in the pressure transducer is 180 deg out of phase from the accelerometer signal, and by adjusting the amplitude of the accelerometer signal, cancellation of the acceleration effect is achieved. A block diagram of such a system is shown in Fig. 75. It is fairly obvious that in a system employing several transducers subject to the same acceleration effects that the output from one accelerometer may be used to compensate all the transducers.

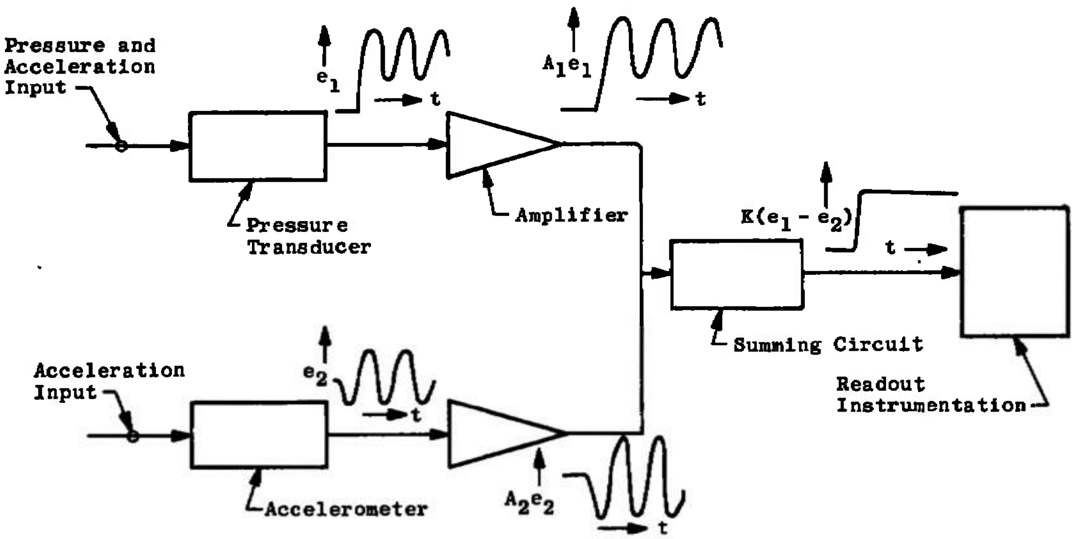


Fig. 75 Block Diagram of System for Compensation of Acceleration Effects in Pressure Transducers

3.2.6 Multiplexing Systems

At times, in applications requiring the measurement of large numbers of pressures, it may be advantageous to employ electrical scanners or "multiplexers" rather than pressure scanners. In general, it may be said that the electrical scanner is easier to use than the pressure scanner and, of course, the pneumatic system is somewhat simpler. Pressure scanners are somewhat notorious for their pressure leakage problems and they are limited in both the pressure ranges which they cover and their maximum speed of operation; whereas none of the foregoing problems is significant in the multiplexer system. Cost considerations between the two systems vary and must be treated individually.

A typical multiplexing system is made up of groups of electronic switches, amplifiers and analog-to-digital (A-to-D) converters which allow many analog signals to be processed into a single digital output (131). The digital information obtained is usually processed in a digital computer and has various mathematical operations performed on it. Shown in Fig. 76 is a block diagram of a typical system. The analog input signal is brought into a differential low level multiplexer which switches the individual channels into a preamplifier. These differential inputs are often subgrouped as shown. The single-ended output of the amplifier is multiplexed into a sample and hold by the high level multiplexer. The output of the sample and hold is connected to an A-to-D converter, which converts the analog signal into a parallel digital word which can be further multiplexed in a digital multiplexer. The output of the digital multiplexer is then connected to the computer. The total number of channels for the system described is given by L x M x N, where L is the number of analog inputs in one group, M is the number of groups of low level inputs, and N is the number of A-to-D converters which are interfaced.

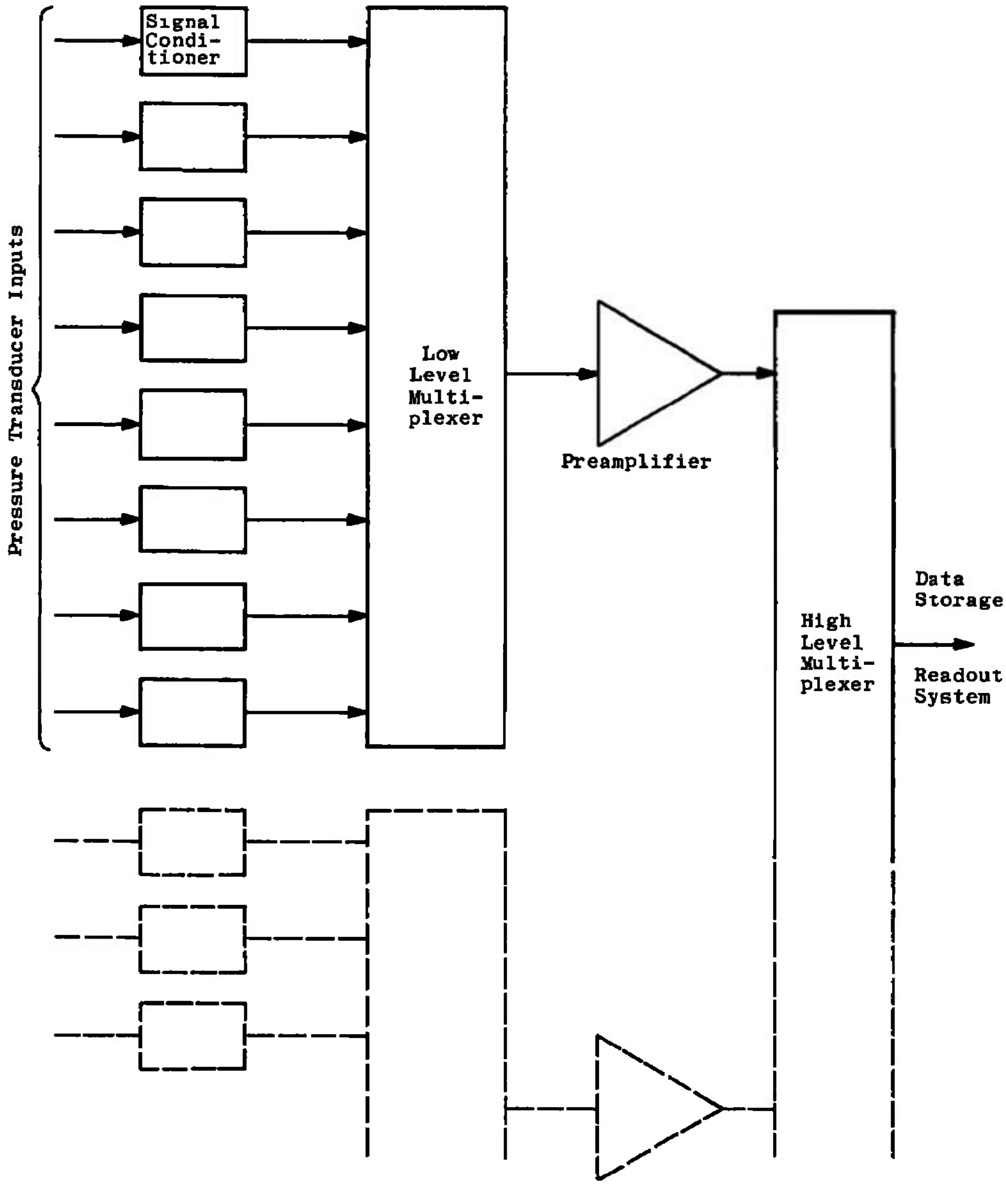


Fig. 76 Block Diagram of Multiplexing System

The low level multiplexing system is the most difficult to achieve, because noise, cross talk, and common mode rejection limit the accuracy of the low level signals. One approach uses a separate differential amplifier per channel and has the advantage of high input impedance. However, the increase in cost of the system, due to separate amplifiers, is often prohibitive for a large number of channels. Another approach uses a transformer coupling method to convert the differential signal into a single-ended AC modulated signal. This approach has lower cost per channel because of the reduction in the total number of amplifiers; however, the input coupling arrangement creates a low input impedance.

High level multiplexing systems are considerably easier to achieve than the low level type, particularly with the advent of the field effect transistor. The simplest, fastest, and most accurate multiplexer of all is the digital multiplexer, which is achieved completely with digital logic circuits.

The analog input signal defines the overall performance required of the system in terms of throughput rate. Shannon's sampling theorem (131) states that a signal must be sampled at a rate at least twice the maximum frequency component in order to faithfully reproduce it. The high speed restriction on the system is given at the digital output of the digital multiplexer by the maximum rate at which the information can be processed.

When many channels of a multiplexer are connected together, performance parameters, such as settling time, cross talk, and noise are affected. In the case of settling time and cross talk, the performance is degraded proportional to the number of channels connected together because of added capacitance. Noise, on the other hand, is increased when submultiplexing is used.

Instrumentation systems are manufactured today with accuracies of 0.01 percent and throughput rates of 100 kHz, which require circuits capable of settling a 10-v step input to 1 mv within 5 to 10 μsec. Although accuracy-speed performances of this level can be achieved in the electronic system, it is to no avail if the implementation of the system into the overall instrumentation problem is not carefully thought out. Factors that must be considered to achieve an effective overall instrumentation performance are:

Input Impedance versus Source Resistance
Common Mode Errors versus Frequency and Source Unbalance
Systems Speeds
Noise versus Bandwidth

3.2.7 Data Recorders

A wide variety of instrumentation is available for recording the outputs from pressure transducers. Since the output from the transducer and its adjunct signal-conditioning equipment is generally a voltage which is proportional to the pressure applied to the transducer, the recording instrumentation is basically a voltmeter. Many factors can influence the selection of the readout or recording instrumentation; some of these criteria are (1) number of simultaneous channels required, (2) the dynamic measurement range or resolution, (3) precision required, (4) response time or frequency response, (5) whether or not signal (data) storage is required, (6) whether the signals are to be recorded in digital or analog form, and, of course, (7) the cost per channel.

The number of data channels required is determined by the number of pressure measurements required and whether multiplexer or pressure switches are used. This in turn is determined largely by the test or measurement time available in the wind tunnel. The dynamic measurement range is the ratio of the maximum pressure that must be recorded relative to the smallest increment of pressure which must be resolved. Precision indicates how closely data may be compared between tests or recordings or how well the system will repeat a measurement.

The required response time is determined by the test or measurement time available and can vary from minutes in the case of transducers with long tubulations between transducer and measuring orifice (Section 3.1.2.2) to times so short as to be measured in microseconds in high performance shock tubes whose run duration is less than a millisecond.

The ultimate use of the data generally determines whether or not the data is stored, and this along with the quantity of data recorded generally determine whether an analog or digital recording device is used. In most wind tunnel applications it is necessary to store the data in some form, and if a substantial quantity of data is involved, A-to-D conversion techniques can be employed to provide simple methods of data storage as well as putting the data in a format which is intrinsically more adaptable and flexible for manipulation by digital computers. Advances in A-to-D conversion techniques have made A-to-D systems the ultimate for data recording with no other system providing a challenge to their accuracy, resolution, speed, and low cost for a large number of inputs. The speed of this type system is rapid enough to use with the highest frequency transducers developed to date.

Table II shows a comparison of typical pertinent features of various recording systems which have fairly widespread use in wind tunnel pressure measurements.

The servobalance recorders are the most accurate analog recorders available today, offering excursions of up to 16 in. The servobalance system in the feedback loop of the recording pen permits accuracies of 0.25 percent without drift or degradation from line voltage and ambient temperature variations. The bandwidth of these systems is about 10 Hz for low amplitude excursions and 1 Hz for wide amplitude or full-scale excursions. Servobalance recorders are usually made in a pressure versus time strip chart form which enables pressure to be plotted as a function of time. Two pen versions of these recorders are available offering two pressures versus time recordings on the same chart.

Mechanical oscillographs use a galvanometer to move an arm through an angular deflection in proportion to the input signal. The angular motion is converted mechanically to rectangular coordinates to simplify viewing and analysis. Because of the relatively high mass and inertia and low natural frequency of the galvanometers, a stage of power amplification is usually required to secure higher effective sensitivities.

Recording light-beam oscillographs, because of the low mass of the galvanometer system and the noninterference of the light beams, enable simultaneous recording of up to fifty data channels on a 12-in. chart. Data up to 1 kHz can be recorded with an 8-in. peak-to-peak amplitude and an 800:1 dynamic range, and data up to 13 kHz with 1-in. amplitude can be recorded.

TABLE II

ANALOG RECORDING COMPARISON

	Servorecording Potentiometers	Oscillograph Mechanical	Oscillograph Light Beam	Recording Oscilloscope	Oscilloscope and Camera	Magnetic Tape, FM	Magnetic Tape, Direct	Analog-to-Digital, Low Speed	Analog-to-Digital, High Speed
Dynamic Range (Without Gain Change)	16 in. 1000/1	2 in. 80/1	8 in. 800/1	5 in. 500/1	4 in. 50/1	(40%) 400/1	50/1	100,000/1	1000/1
Precision of Amplitude Measurement	0.25%	2 %	2 %	3 %	3 %	2 - 5 %	3 db (~30%)	0.01 %	0.01 %
Bandwidth Full-Scale	DC to 1 Hz	DC to 30 Hz	DC to 1 kHz	DC to 100 kHz	DC to 50 MHz	DC to 80 kHz	300 Hz to 1.6 MHz	40 Samples per Second	100,000 Samples per Second
Reduced Amplitude	DC to 10 Hz	DC to 100 Hz	DC to 25 kHz	DC to 1 MHz	DC to 50 MHz	DC to 160 kHz			
Cost per Single Channel or Lowest Initial Price	$1,000	$4,000	$2,000	$15,000	$1,700	$12,000	$12,000	$12,000	$40,000
Cost per Additional Data Channel (Not Time Shared)	$1,000	$1,000	$135	$15,000	$1,700	$800	$800	$80 (In Lots of 25 Channels)	$200 (In Lots of 50 Channels)
Maximum Channels per System (Not Time Shared)	3	8	50	1	2	56	56	25-100	50-100
Notes	Time Shared-Common with Multipoint Systems	Traces Cannot Cross	Traces May Cross						

The recording oscilloscope is an instrument which overcomes the basic electromechanical problems of the galvanometer by writing on photosensitive direct print paper with an electron beam in a cathode ray tube. This enables the data bandwidth to be extended to 100 kHz with 3-in. peak-to-peak deflection and 1 MHz with 0.4-in. deflection of the beam. The limiting factor in the latter case is more the sensitivity of the emulsion rather than the performance of the data electronics.

An oscilloscope and camera provide the same basic capabilities of the recording oscilloscope with the exception that the data trace must be compressed onto a piece of film measuring somewhere in the range of 3-1/2 by 4-1/2 in. One or two channels may be recorded simultaneously. For a few data channels of transient pressure measurements requiring the frequency response of a scope-type instrument, the oscilloscope-camera combination provides the most economical recording system.

Magnetic tape is a slightly different form of recording in that there is nothing visible to the human senses on the recording medium. In a sense, tape is an accurate analog memory system which stores data in the "live" form enabling subsequent re-creation of the test for various types of analysis, simulation and testing. Two basic types of analog recording are used with magnetic tape - Direct and FM.

Direct recording offers a very wide data bandwidth or frequency response and rather poor amplitude stability. The direct technique is most often used for the recording of information that is in the frequency domain where the relative amplitude inaccuracy is unimportant.

Frequency modulation is the most widely used data instrumentation technique in that it is capable of recording wide band, DC to 80 kHz, data with ±5-percent precision.

Conventional tape recording channel capabilities are 14 channels on 1-in. tape, although special systems have been built with as many as 56 data channels on wider tape.

Analog-to-digital systems fall into two major categories: (1) low speed systems for measuring slowly varying or static pressures such as are found in continuous tunnels, and (2) high speed systems used for the measurement of dynamic pressures or highly transient, short duration pressure pulses such as are found in shock tunnels.

4. CALIBRATION TECHNIQUES AND EQUIPMENT

Most instruments used for measuring pressure in modern wind tunnels require calibration. That is, a known pressure or pressures must be applied to the transducing device in order to determine the sensitivity of the pressure measuring system. Whether the calibration pressures applied are static, dynamic, or both will depend on the intended use of the pressure measuring system. Most static calibration standards simply measure an unknown pressure with a high degree of accuracy and reliability. Therefore, they are used to determine the value of the pressure applied to the transducer being calibrated but do not apply the pressure. Methods of applying static calibration pressures are numerous and rather obvious and will not be discussed except for a special case in Section 4.1.1. Application techniques for dynamic pressures are not so obvious, and the sections covering them will emphasize the application rather than the standard.

4.1 Static Calibrations

It is quite common practice in calibrating wind tunnel pressure measuring systems to use another pressure measuring system which has been carefully calibrated as a calibration standard. This is usually done because of the tedium involved in using more ideal pressure standards.

The ideal standard for making static pressure calibrations would be completely insensitive to environmental changes, and its characteristics would be stable and calculable (from basic quantities such as mass and length) to a high degree of accuracy. No such instrument exists; however, some are available which have predictable or correctable sensitivities to environmental changes. Notable among them are the McLeod gage, the liquid manometer, and air and oil deadweight testers (piston gages). Bourdon tubes and other pneumatic-mechanical gages require a calibration against another standard, but are considered suitable for calibration of pressure transducers.

The pressure ranges of the calibration standards to be discussed are shown graphically in Fig. 77. These ranges are not intended to be exact but to show only the general range of applicability. The term bourdon tube gage as mentioned earlier includes not only bourdon tubes but also bellows, diaphragms, and other pneumatic-mechanical gages. The McLeod gage is the only one of the five which is strictly an absolute pressure device. Liquid manometers, bourdon tube gages, and air deadweight testers can be used as absolute, differential, and gage pressure instruments, depending on the reference pressure applied. The oil deadweight tester could conceivably be used the same way; however, the authors do not know of them being so used. They are generally gage pressure instruments.

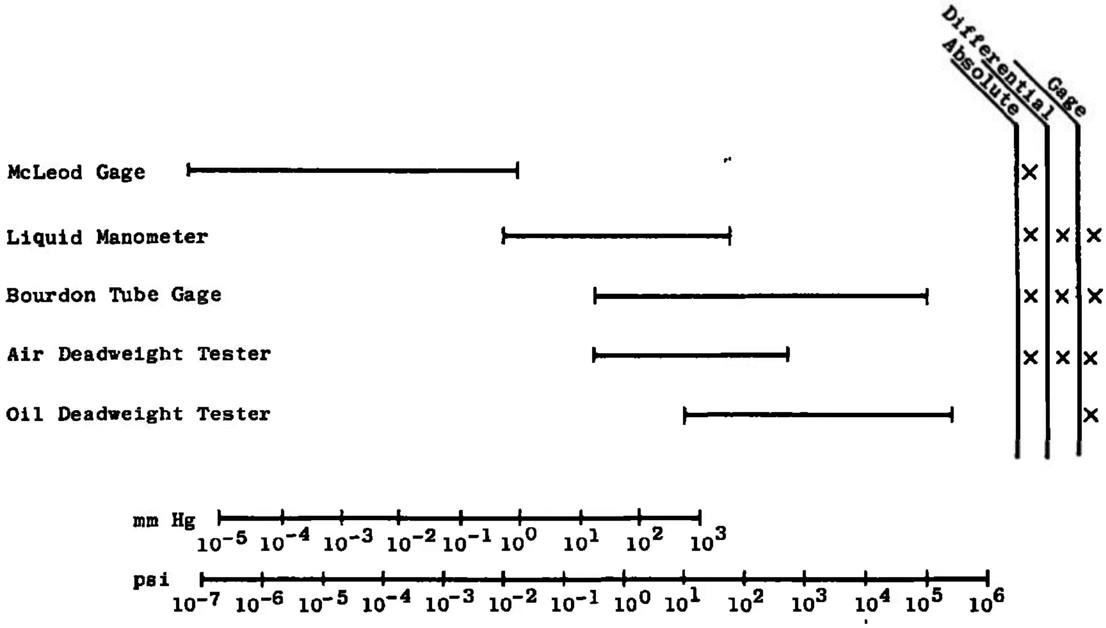


Fig. 77 Pressure Range of Some Calibration Standards

The error of these calibration standards is shown graphically in Fig. 78. The values indicated are minimum errors given by various manufacturers and laboratories and somewhat larger errors can be expected unless great care is taken in using the instruments. The ranges of error do not necessarily coincide with the pressure ranges of Fig. 77. Frequently a manufacturer or laboratory will not quote errors over the full range of the instrument.

The reader is probably familiar with the principle of operation of these calibration instruments or standards; however, a brief explanation of each will be given for completeness.

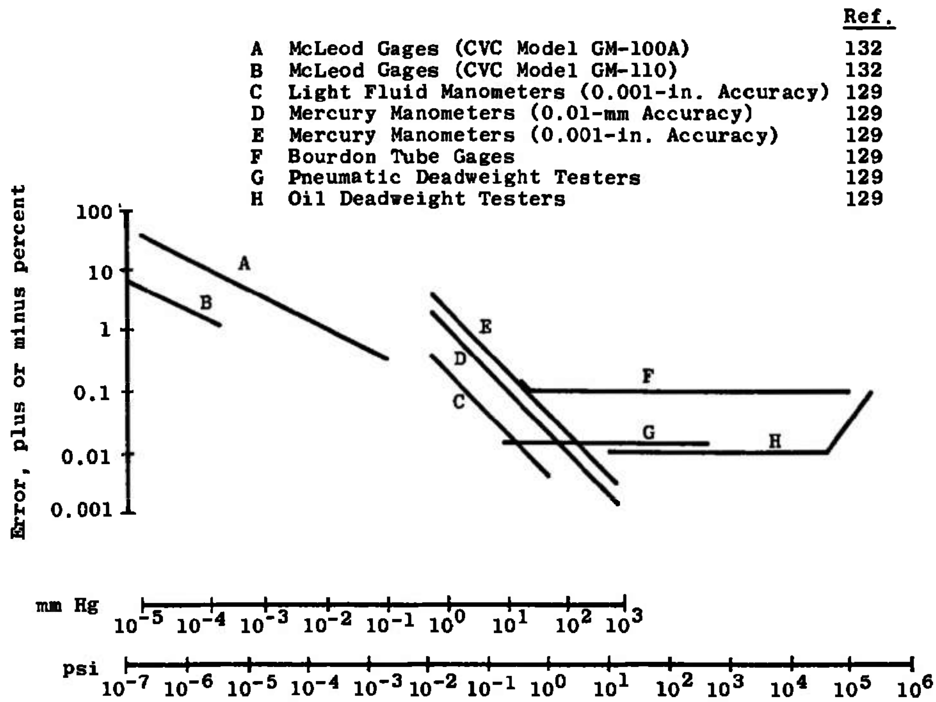


Fig. 78 Minimum Error of Some Pressure Calibration Standards

4.1.1 McLeod Gage

The McLeod gage (133) takes a known volume of gas at the unknown initial pressure and compresses it to a much smaller volume and higher pressure; both are measurable. With the values of the final pressure, the volumes, and Boyle's Law, the unknown pressure can be computed:

$$p_{unknown} = \frac{V_{final}}{V_{initial}} p_{final} \tag{27}$$

A simplified diagram of a McLeod gage is shown in Fig. 79. Mercury is generally used to compress the sample of the gas and also to measure the final pressure.

With the nomenclature of the system shown in Fig. 79, the pressure, p_1, to be measured is (133):

$$(p_1 + h)bh = p_1 V \tag{28}$$

where p_1 and h are in mm Hg

$$p_1, \text{ mmHg} = \frac{bh^2}{V - bh} \tag{29}$$

The most common source of error, other than those associated with the physical parameters of the McLeod gage, is condensible vapors in the system. The most probable condensible is water vapor, which has a vapor pressure of approximately 17 mmHg at room temperature. During operation of the McLeod gage as the sample is being compressed, any water vapor present will be condensed, if the

vapor pressure is exceeded; thus, the pressure measured will be lower than the actual pressure. This problem can be avoided by heating the gage to raise the vapor pressure above the final pressure in the gage, or placing a dryer in the vacuum line between the gage and system. Desiccant-type dryers help alleviate the problem, but a cold trap at cryogenic temperature is a more reliable solution.

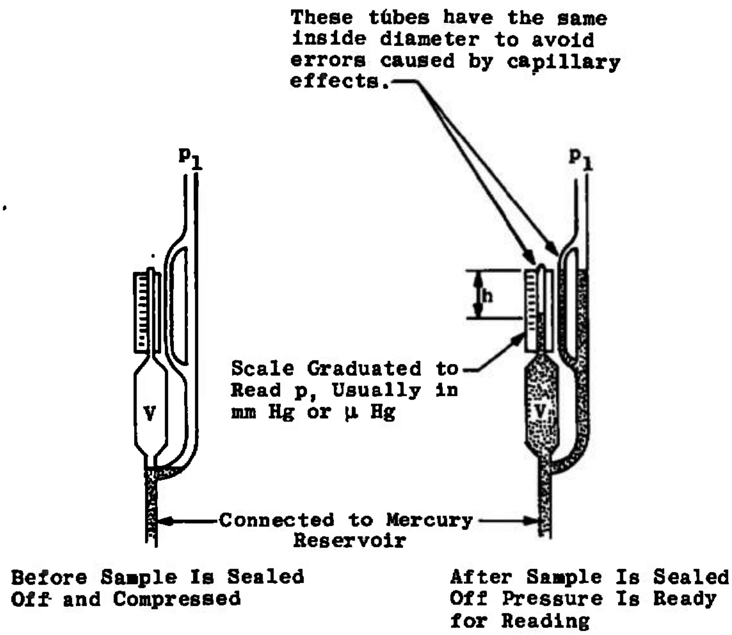


Fig. 79 McLeod Gage

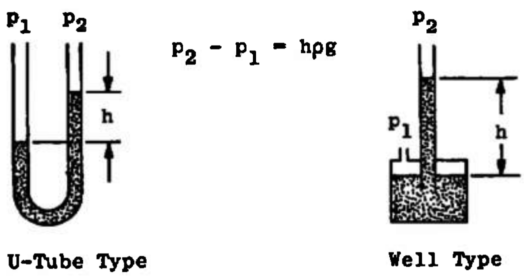


Fig. 80 Commonly Used Liquid Manometer Types

A novel device which deserves comment here is a calibrator which is the "inverse" of the McLeod gage. The calibrator, making use of Boyle's law, transfers known mass increments of the working gas into an initially evacuated vessel of known volume to produce the known pressure steps. Pressure steps of 10^{-3}, 10^{-2}, 10^{-1}, or 1 mmHg can be produced by the version of the device described in (134 and 135). It works well at low pressures where other instruments may be either inaccurate or tedious to use, or both. Accuracies on the order of one percent are attainable with this calibrator even at the 10^{-3}-mmHg pressure step.

4.1.2 Liquid Manometer

The liquid manometer works on the principle that a given pressure will support a column of liquid of a certain height:

$$p_2 - p_1 = h\rho g \qquad (30)$$

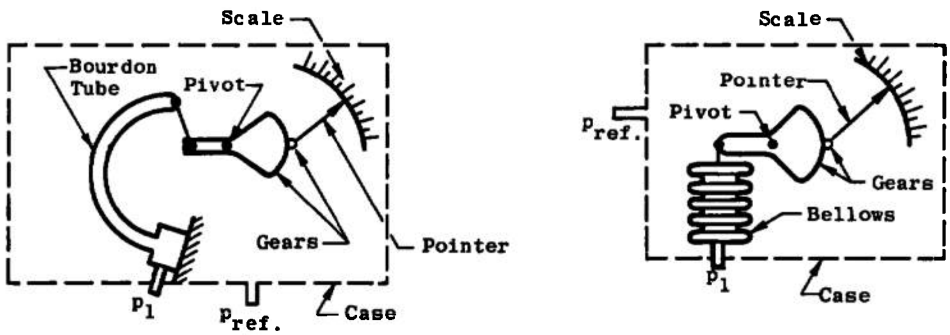
where g is the ratio of acceleration to local acceleration due to gravity. As shown in Fig. 80, the manometer can take on two basic forms: the U-tube and the well type. As previously stated, the manometer measures absolute, differential, or gage pressure, depending on the reference pressure applied. There are several factors which affect the accuracy in addition to the obvious direct effects of

the accuracy of the column height and density. The specific weight ρg is a function of both temperature and local acceleration of gravity. Capillary effect errors enter directly into the pressure error and add to or subtract from the pressure indicated by the column height. Capillary errors are generally thought of as wholly a function of the liquid surface tension and the tube diameter. Contaminants on the tube walls and in the liquid can also contribute to these errors. Temperature effects on the column height measuring apparatus must also be considered. Vertical alignment of the manometer is important as well as compressibility effects on the liquid density. Commercially available precision liquid manometers have features to compensate or to correct for the significant errors from various sources.

Reference (129) contains a good general compilation of commercially available liquid manometers and a discussion of sources of manometer errors and the accuracies obtainable. Accuracy beyond the accepted maximum can be obtained using the procedures and apparatus described in (136). Light oil (specific gravity ≈ 1) in combination with an optical system to detect the meniscus and a precision lead screw arrangement to measure the liquid column height have been used to attain accuracies of approximately 1 μ Hg (136).

4.1.3 Bourdon Tube Gages

As mentioned previously, the term bourdon tube is used to include bourdon tubes as well as other pneumatic-mechanical devices. Bourdon tubes, bellows, diaphragms, or other pressure sensitive mechanisms are used to deflect a pointer. Two representative configurations are shown in Fig. 81.



a. Bourdon Tube b. Bellows

Fig. 81 Bourdon Tube Gages

Many of the better quality gages have sufficient mechanical amplification to allow the pointer to make several revolutions around the face of the instrument, thus increasing the resolution or readability. Reference (129) describes several commercially available bourdon tube gages suitable for calibration of wind tunnel pressure measuring systems.

4.1.4 Deadweight Testers

Deadweight testers or piston gages use a known force and area to produce a known pressure. The force is applied by placing weights on the vertical piston-cylinder, thus the terminology "deadweight tester." Both air (or other gases) and oil are used as the working medium. The general arrangement of a deadweight tester is shown in Fig. 82. Air testers are available with an enclosure to allow control of the reference pressure. The piston is rotated or oscillated during operation to reduce the errors

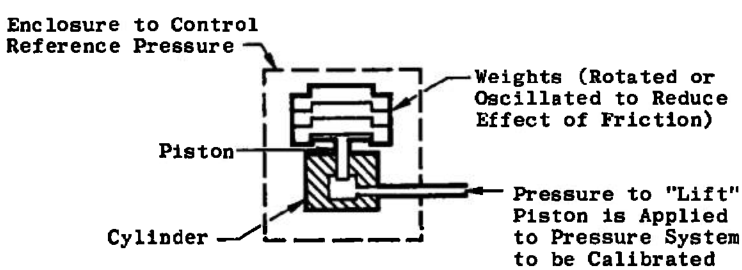


Fig. 82 General Configuration of Deadweight Tester (Air or Oil)

caused by piston-cylinder friction. The mass of the weight, the local acceleration of gravity, and the effective piston diameter (usually the mean between the piston and cylinder diameters) must be known to determine the pressure. In addition to friction, there are several other factors which cause errors in deadweight testers: some are unique to low, some to high pressures, and some to both. Buoyancy of the weights and piston, and the head of the fluid when the tester and instrument being calibrated are not at the same level are of importance at low pressures. Piston-cylinder distortions attributable to pressure and solidification of the oil must be considered at high pressures. Reference (129) should be consulted for details and manufacturers of deadweight testers.

4.2 Dynamic Calibrations

4.2.1 Time Domain Calibrators

Time domain calibrators are generally used for one or more of the three following purposes:

1. To measure the rise time to a step function of transducer or transducer plus connecting tubing and other installation volumes.
2. To obtain time domain data on transducers or transducer/acoustic mounting combinations which can be analyzed to produce frequency response data (Section 4.2.3).
3. To obtain transducer calibrations when the static and dynamic sensitivities are not equal or when the transducer-signal conditioning-recording system does not respond to static loads, e.g., piezoelectric transducers and/or AC-coupled signal conditioning-recording equipment.

Time domain pressure calibrations almost exclusively produce step functions with some finite rise time. They are generally of two types:

1. Shock tubes which make use of a shock wave propagating through a fluid or reflecting from a surface to produce a step rise in pressure. The rise time of such a step function is generally negligible as compared to the rise time of even the fastest response transducer. However, the duration of the step is limited from a few milliseconds to several tens of milliseconds.
2. Fast opening devices, either valves or rupture diaphragms, which apply a new pressure to some initial condition on the transducer. The fastest of these devices have rise times on the order of a few hundred microseconds. The duration of the step easily can be made infinite.

The accuracy of the step size for both types of calibrators can be known and is limited mostly by the amount of care the experimenter desires to exercise in measuring initial conditions. There are two other time domain calibrators which warrant attention but do not produce step functions. They produce time-varying pulses. These devices are generally used in conjunction with a reference transducer which is assumed to measure the true pressure pulse. These devices are:

1. Explosive devices which make use of the pressure rise from the burning of an explosive charge in a confined chamber.

and

2. Drop test calibrators which drop a weight on a plunger in a cylinder which is connected to a hydraulic system. The impact of the weight on the plunger produces a pulse in a hydraulic system. The transducer to be dynamically calibrated and a reference transducer are connected to the hydraulic system.

A summary of the characteristics of some of these devices is given in Table III, and a brief description is given in the following subsections.

4.2.1.1 Shock Tubes

A brief explanation of a shock tube and its operation will be given here for those readers who are not familiar with them. A simple shock tube as would be used to calibrate pressure transducers and transducer installations would have two chambers with different pressures separated by a diaphragm (Fig. 83). The chamber containing the high pressure of the two might be simply the room in which the shock tube is located. When the diaphragm is ruptured, either by a plunger or by overpressure, a shock wave propagates down the driven tube as indicated by the line between regions 1 and 2 on the wave diagram of Fig. 83. A transducer located on the wall of the driven tube would see a pressure rise of $p_2 - p_1 = \Delta p_2$, as the shock wave passed. One mounted on the end wall would see a somewhat higher pressure, $p_5 - p_1 = \Delta p_5$, as the shock wave reflected from the tube end wall. These pressures for air in the driven tube can be computed from the following equations (143).

$$\Delta p_2 = p_2 - p_1 = p_1 \frac{7}{6} (M_s^2 - 1) \tag{31}$$

$$\Delta p_5 = p_5 - p_1 = \frac{7}{3} p_1 (M_s^2 - 1) \left[\frac{2 + 4M_s^2}{5 + M_s^2}\right] \tag{32}$$

The equations are restricted to an ideal gas with a $\gamma = 1.4$. Data for imperfect air at $M_s = 1$ to 10 are given in (146). As is obvious from Eqs. (31) and (32), all that is required to determine the Δp's in air is p_1 and M_s. The term p_1 can be measured with any one of many precision manometers, and M_s can be determined from the shock velocity, U_s, and speed of sound, a_1, in the 1 region.

$$M_s = \frac{U_s}{a_1} \tag{33}$$

The shock velocity (U_s) can be computed from the time required for the shock wave to travel between two points a known distance apart. Thin-film heat-transfer gages are probably the best shock detectors for an instrumentation shock tube, although fast-rise-time pressure transducers may also be used. The thin-film gages are fast-response surface temperature transducers and thus will sense a temperature rise caused by the increased heat-transfer rate behind the shock wave. They can be constructed by painting or depositing a platinum or other metallic film on an insulation such as glass or quartz (147 and 148). The time measurements can be made with a high speed counter or by comparing the time with a precision time-mark generator by displaying both on an oscilloscope. Considerable comparison accuracy can be had by using an oscilloscope with a raster trace display, such as a Tektronix Model 535A with the raster modification.

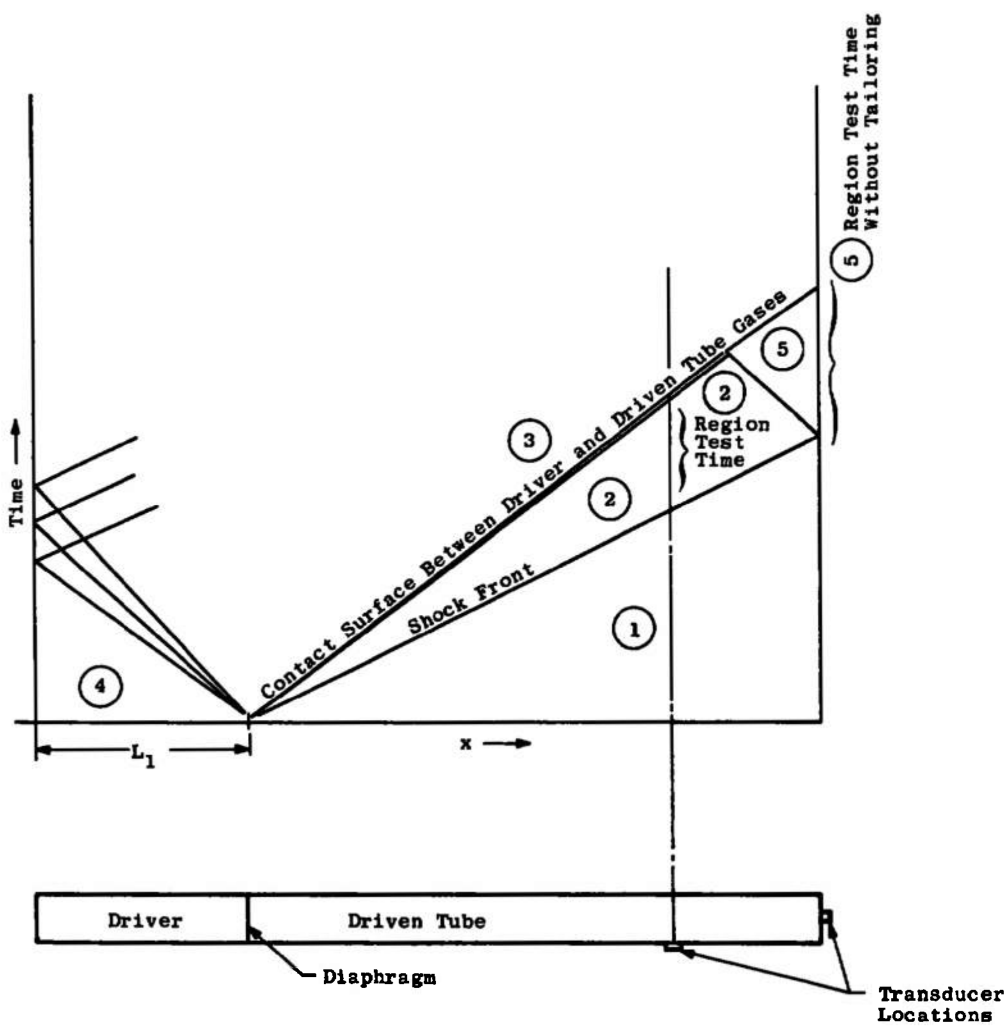


Fig. 83 Shock Tube and Wave Diagram

TABLE III
TIME DOMAIN CALIBRATORS
SHOCK TUBES

	Length		Inside Dimensions	Gas		Maximum Driver Pressure	ΔP Range	Ref.	Facility
	Driver	Driven Tube		Driver	Driven Tube				
1	7 ft	15 ft	1.375 sq in.	Air	Air	600 psi	10 to 410 psi	137	JPL
2	12 ft	8 ft	3 sq in.	He	Air	>600 psi	6 to 1000 psi	138	NBS
3	---	15 ft	3-in. ID	Air	Air	1 atm	---	---	Lockheed-Georgia
4	1 ft	6 ft	2-in. ID	He or N_2	Air	1400 psi	32 - 1050	139	BRL
5	2 ft	~8 ft	2.5-in. ID	He or Air	Air	~100 psi	1 to 100	---	VKF/AEDC

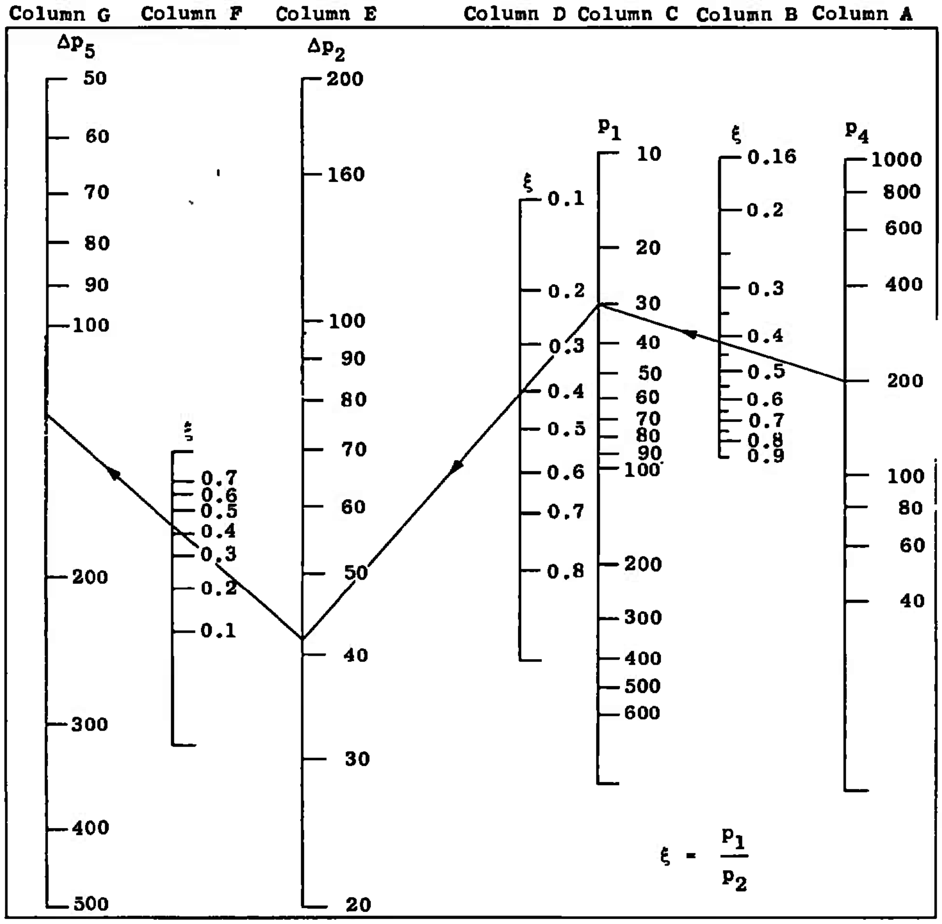
FAST OPENING DEVICES

	Type	Rise Time	ΔP Range	Ref.	Facility
6	Poppet-Valve, Solenoid Operated	3 msec 1 msec	<10 mm Hg >10 mm Hg	140	NPL
7	Poppet-Valve, Solenoid Operated	0.5 msec	5 to 100 mm Hg	141	RAE
8	Poppet-Valve, Drop-Weight Operated	120 μsec	---	142	NOL
9	Poppet-Valve, Drop-Weight Operated	~1 msec	1 mm Hg to 25 psi	---	Lockheed-Georgia
10	Poppet-Valve, Liquid Test Medium	25 μsec for 23,500 psi	50,000 psi	143	NBS
11	Solenoid Valve (ANSCO No. X831428)	---	Max. 100 psi	139	BRL
12	Solenoid Valve (Make and Model Unknown)	---	Max. 2000 psi	139	BRL
13	Solenoid Valve (Hoke No. B90A320R, 2-Way)	~20 msec	Max. 2000 psi	---	VKF
14	Solenoid Valve (Make and Model Unknown)	~1 msec	2 to 2000 psi	138	NBS
15	Burst Diaphragm	<0.5 msec	Up to 1 psi	---	Lockheed-Georgia
16	Burst Diaphragm	0.25 msec	Up to 200 psi	144	JPL
17	Burst Diaphragm (Liquid Medium)	0.013 msec	60 psi	145	NOL
18	Burst Diaphragm	---	---	51	VKF/AEDC

NON-STEP FUNCTION DEVICE

		Approximate Shape	Pulse Duration	ΔP Range	Ref.	Facility
19	Drop Test Calibrator (Hydraulic)		10 msec	Up to 50,000	139	BRL

Figure 84 is a nomograph (137) which can be used to set the initial condition to obtain desired Δp's for air-to-air operation, i.e., air as the gas for both chambers. Using helium as a driver gas will give higher shock wave speeds and thus higher pressure on the side and end walls of the driven tube.



(Figure Reproduced through Courtesy of Jet Propulsion Laboratory, JPL Report No. 20-87)

Fig. 84 Nomographs Relating Chamber Pressures, Shock Strengths, and Pressure Steps

The duration of the pressure step is a function of many factors, e.g., driver length, driven tube length, and shock strength (p_1/p_2). Figures 85 and 86 (137) are helpful in determining pressure step duration.

The pressure step duration on the end wall can be extended considerably by operating the shock tube in a tailored condition. When tailored, the reflected shock wave is transmitted through the contact surface and not reflected back to the end wall. This happens when $a_3 = a_2$ and $\gamma_3 = \gamma_2$. For He/air, both at 300°K, this is achieved for $M_s \cong 3.6$ and for H_2/air, $M_s \cong 6$. The rise time of the pressure step generated by a shock tube is $<< 1\mu$sec for the operating condition usually used. However, the apparent rise time to a transducer mounted in the side wall is equal to

$$\Delta t = \frac{\text{Transducer Diameter}}{\text{Shock Velocity}} \tag{34}$$

It can be readily seen that for low M_s and practical transducer diameters the rise time may be several microseconds.

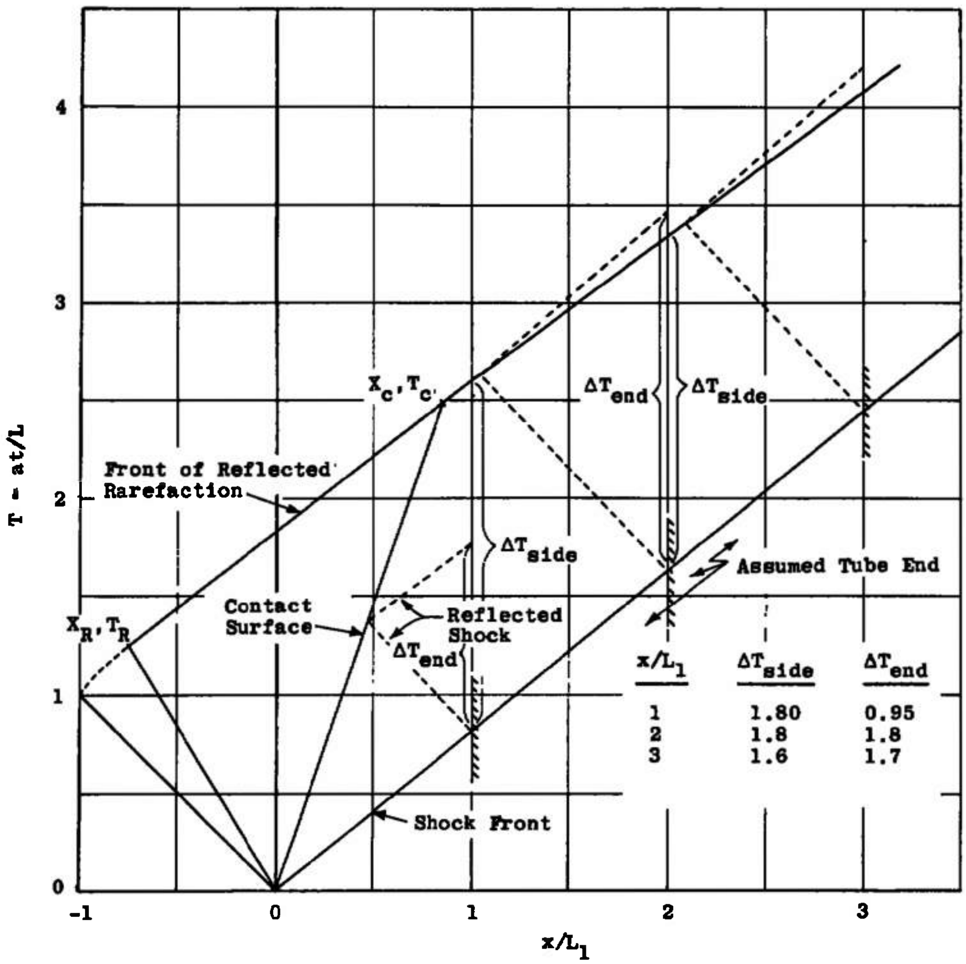


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Fig. 85 Time-Distance Plot of Waves in Any Shock Tube for $\xi = 0.65$

Both plastics and metals are used for diaphragms. As previously mentioned, they are ruptured either by overpressure or by a plunger or knife. The AEDC/VKF 2-1/2-in. -ID shock tube (No. 5, Table III) uses the overpressure technique on multiple thicknesses of DuPont Mylar® polyester. This particular diaphragm arrangement has a rupture pressure of approximately 20 psid (Δp across diaphragm) per 0.001-in. thickness of Mylar®.

For more complete information on theory and use of shock tubes, the reader is referred to (149), (150), and (151).

4.2.1.2 Fast Opening Devices

A number of fast opening devices have been reported in the literature (51 and 138 through 145). By some scheme, all apply a new pressure level to the initial static pressure on the transducer. The fastest of these devices uses either a burst diaphragm or a fast opening valve constructed for minimum volume between the diaphragm or valve and the transducer. The slower ones use commercailly available solenoid valves.

Typical poppet-valve calibrators are shown in Figs. 87 (140) and 88 (142). Others are described in (140), (141), (142), and (143). All use either a solenoid or a drop weight to open the valve. It can be seen in the figures that the devices produce a step by venting the volume to which the transducer is connected to a much larger volume at a different pressure. The pressure in the larger volume is the final pressure on the transducer.

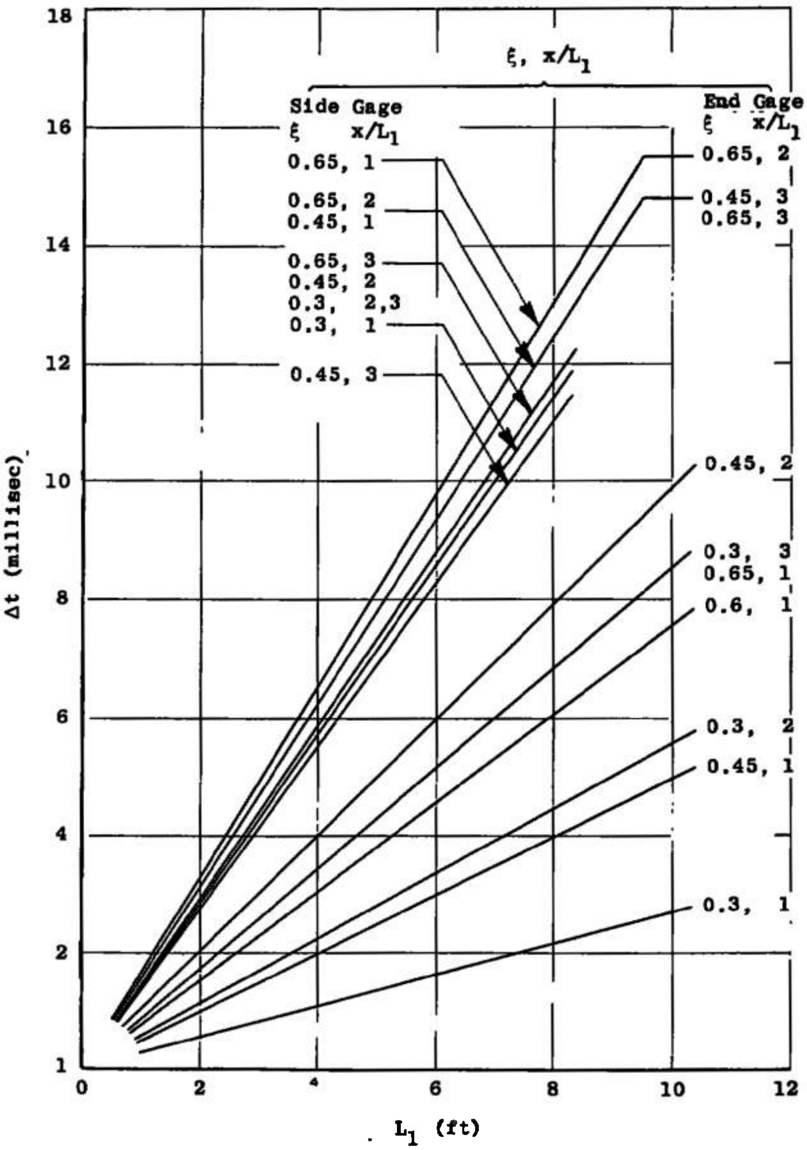

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Fig. 86 Chamber Lengths vs Constant-Pressure Intervals Δt

Solenoid valve calibrators are basically the same as the poppet-valve devices but use a commercial valve. Thus, the operation is not as fast, and the volume is usually larger as compared to the poppet-valve, and thus the step is generally slower to rise to its final value. Typical solenoid valve calibrator schematics are shown in Fig. 89.

The burst-diaphragm devices apply a step pressure in the same manner as the poppet-valve and solenoid valve devices but rupture a diaphragm rather than open a valve. The lower pressure devices usually use a tightly stretched thin rubber diaphragm which will rupture by its prestress when punctured rather than by the pressure differential across it, as in the case of the higher pressure devices. The higher pressure devices use an acetate, Mylar®, or thin metal diaphragm. Typical burst-diaphragm devices are shown in Figs. 90 (51) and 91 (145). The NOL device shown in Fig. 91 uses oil between the diaphragm and the transducer, which explains its fast rise time as compared to pneumatic devices as indicated in Table III, item 17.

4.2.1.3 Drop Test Calibrator

The drop test calibrator (Fig. 92) reported by BRL (139) is so named because a weight is dropped on a piston in a hydraulic unit, thus producing a pulse pressure input to transducers connected to the unit. Even though the calibrator does not produce a step pressure input, it is very useful for comparing

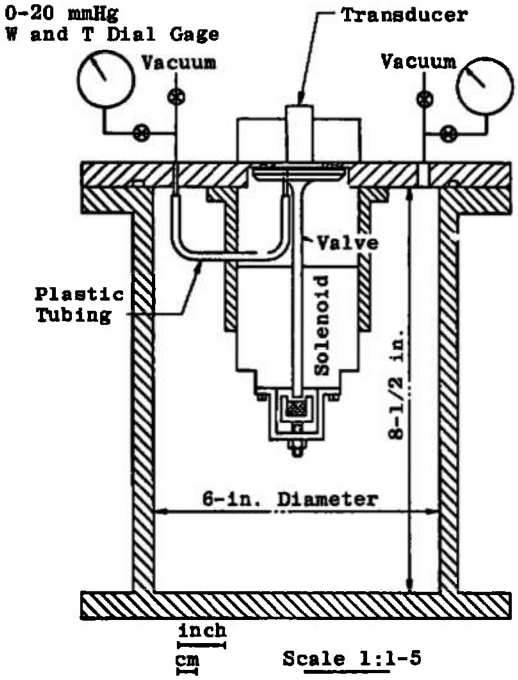

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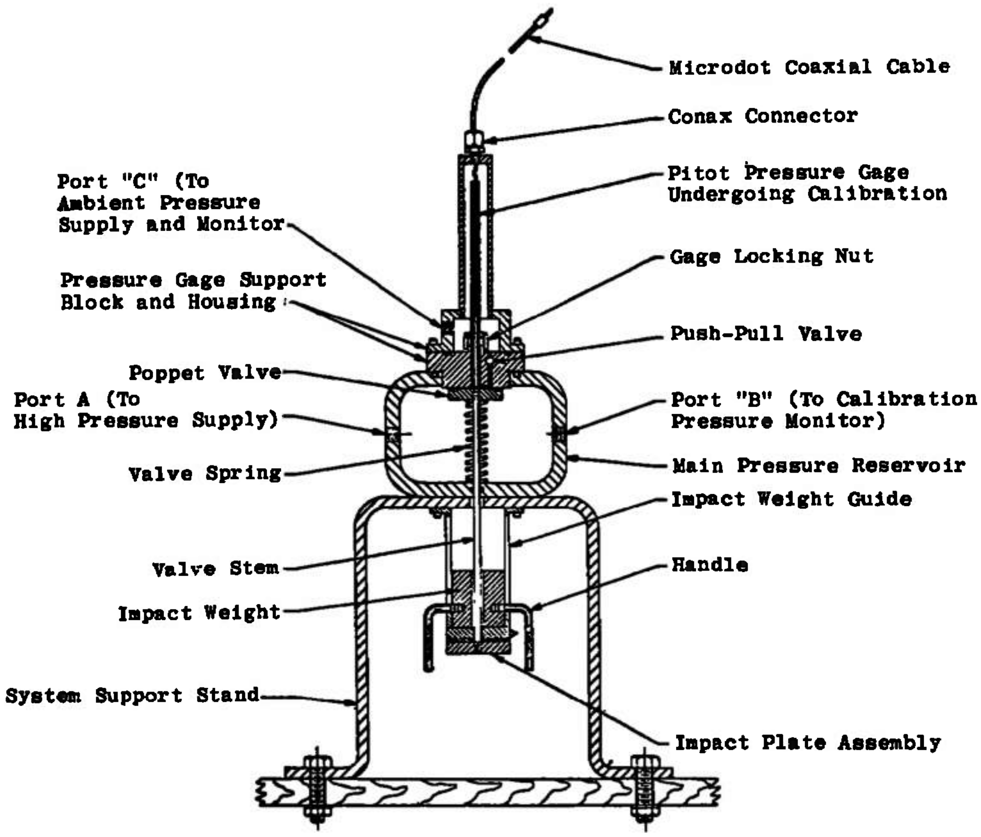
Fig. 87 Pressure Pulse Generator (Sectioned View)



(Figure Reproduced through Courtesy of U. S. Naval Ordnance Laboratory, NOLTR 63-143)

Fig. 88 NPL Semi-Dynamic Pressure Calibrator

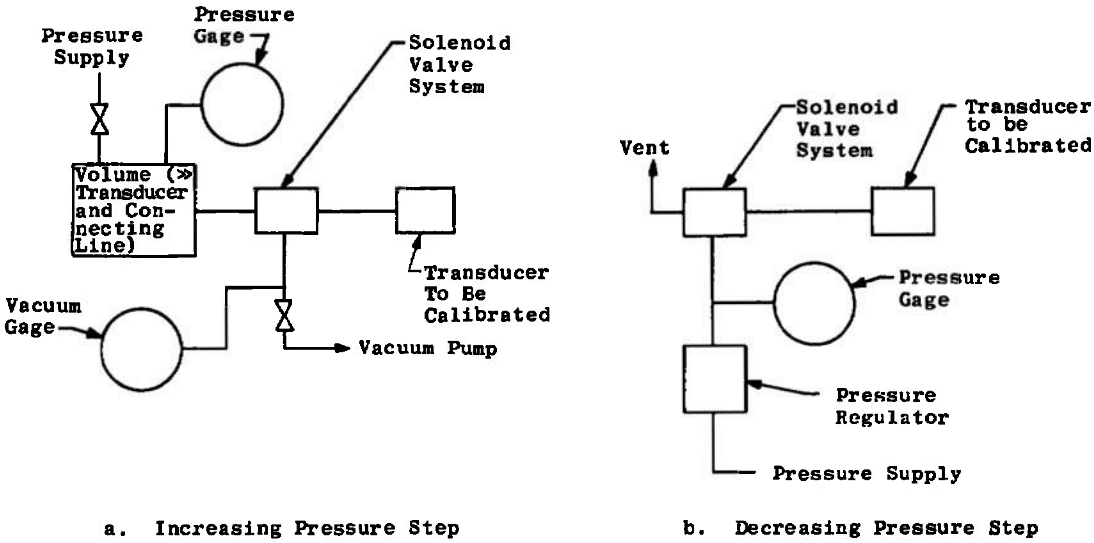


Fig. 89 Typical Solenoid Valve Calibrator Schematics

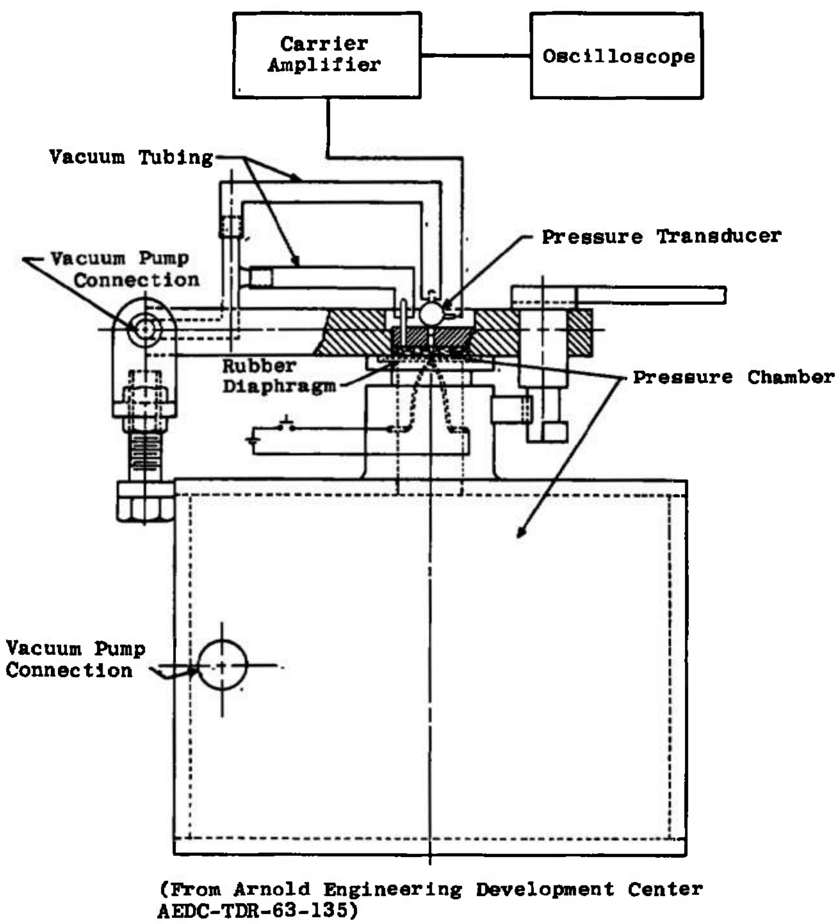
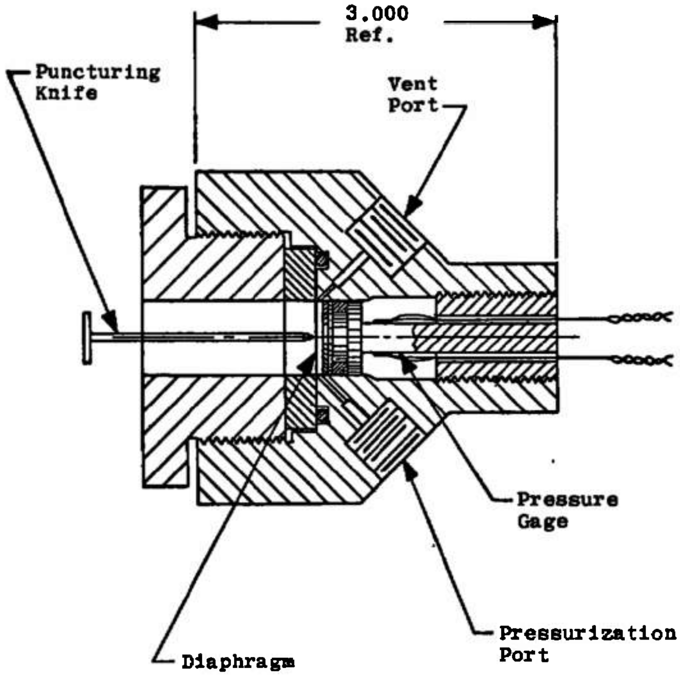


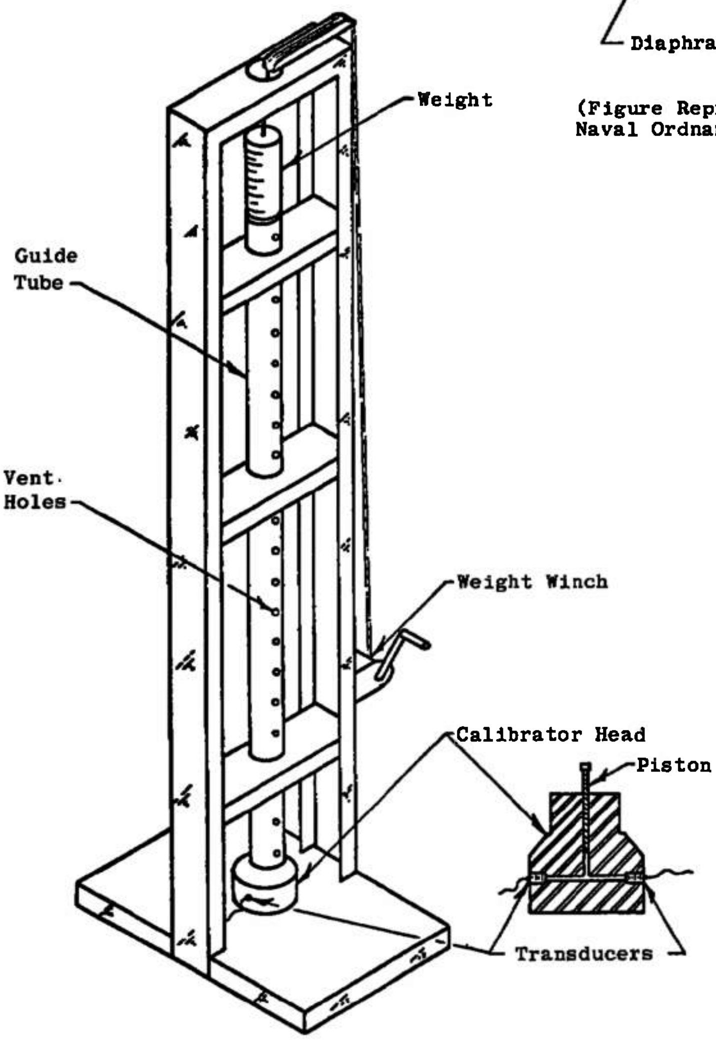
Fig. 90 Low Pressure Step-Function Generator

one or more transducers with a reference transducer of known dynamic characteristics. Its outstanding advantage is the relative ease and safety with which pulses of up to 50,000 psi can be produced as compared with shock tubes and valve calibrators. Figure 93 shows a typical oscillogram of the output signals from two pressure transducers exposed to a pressure pulse from this calibrator. The transducers are gaged-diaphragm strain-gage transducers. One is flush mounted, the other is recessed, and the void is filled with silicon potting compound. The comparison is to evaluate the effect of recessing and filling the void with potting.



(Figure Reproduced through Courtesy of U. S. Naval Ordnance Laboratory, NOLTR 62-218)

Fig. 91 Calibrating Block



(Figure Reproduced through Courtesy of Ballistics Research Laboratory, Memorandum Report No. 1843)

Fig. 92 Drop Test Calibrator

4.2.2 Frequency Domain Calibrators

Frequency domain calibrators are used to dynamically calibrate pressure transducers when the amplitude and phase characteristics as a function of frequency are desired. For the most easily interpretable data, the calibration should produce a pure sinusoidal pressure variation of known amplitude and phase at the inlet of the device to be calibrated. Unfortunately, most of the commonly used calibrators generally produce badly distorted waveforms, especially at high frequencies and high peak-to-peak pressures. If the peak-to-peak pressure is more than a few percent of the ambient pressure, then distortion is almost unavoidable because of the inherent nonlinearity of the process. Futhermore, with a few exceptions (e.g., reciprocity calibrators, electrostatic actuators, and certain pistonphones) all the commonly used frequency domain calibrators require a reference transducer with known characteristics to determine the input pressure to the transducer being calibrated. In other words, the calibrator only furnishes a mechanism to

transfer the calibration from one transducer to another. A representative list of calibrators and calibration techniques in common use are listed in Table IV. A brief discussion of these follows.

The various frequency domain calibrators are divided into four major categories: (1) resonant cavities, (2) nonresonant cavities, (3) valve calibrators, and (4) microphone calibrators. Some of the calibrators might easily fall into more than one category, but for convenience they will only be placed in what seems to be the most appropriate one.

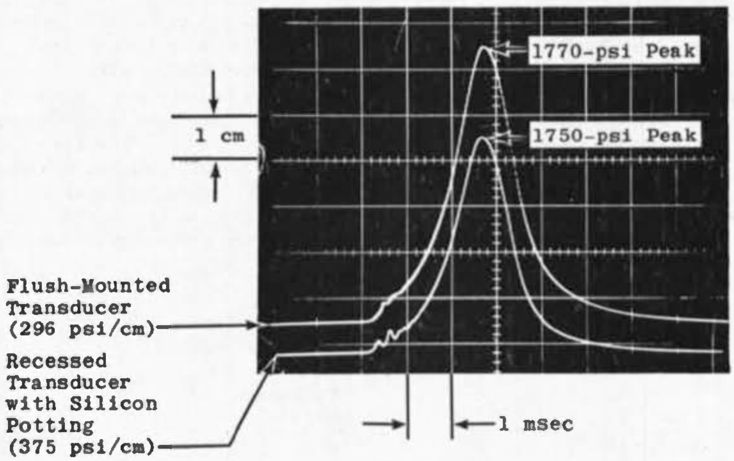


Fig. 93 Transducer Signals from Drop Test Calibrator

TABLE IV

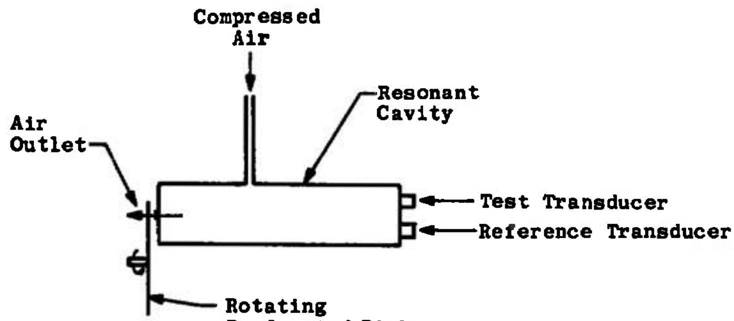
FREQUENCY DOMAIN CALIBRATORS

	Type	Pressure		Wave Form	Frequency Range	Ref. No.
		Mean	Dynamic			
1	Rotating-Valve Generator		10 to 15 psi	Square	Up to 10 Hz	143
2	Tuned Cavity - Siren Driven		30 psi	Sawtooth	50 to 1000 Hz	143
3	Tuned Cavity - Piston Driven (Hydraulic)	500 psi	±100 psi	Sinusoid	10 to 1000 Hz	143
4	Pistonphone - Motor Driven	1 atm	±10 in. H_2O	Sinusoid	0 to 70 Hz	152
5	Princeton Sinusoidal Pressure Generator	250 psi	Peak-to-Peak 130 to 10 psi	Sinusoid	Up to 10 kHz	153
6	Pistonphone - Motor Driven		Peak-to-Peak 1 to 3 psi	Sinusoid	1 to 200 Hz	154
7	Horn Driven		Up to 1.125 psi	Sinusoid	200 to 10 kHz	154
8	Horn Driven		140 db	Sinusoid	10 to 100 kHz	154
9	Circular Resonant Chamber Excited with Rotating Jet	1 atm	2.5 psi	Sinusoid	Up to 700 Hz	155
10	Pistonphone - Nonresonant	5,000 psi	Peak-to-Peak 40 psi	Sinusoid	Up to 2,000 Hz	155
11	Cam-Type Pulsator		±3 psi	Sinusoid	Up to 5 kHz	156
12	Rotating Disk (Slotted)	1 atm	1 in. Hg	Square	---	157
13	Horn Driven	1 atm	140 to 150 db	Sinusoid	20 to 10 kHz	AEDC
14	Pistonphone - Model Airplane Engine	1 atm	170 to 180 db	Sinusoid	5 to 85 Hz	AEDC

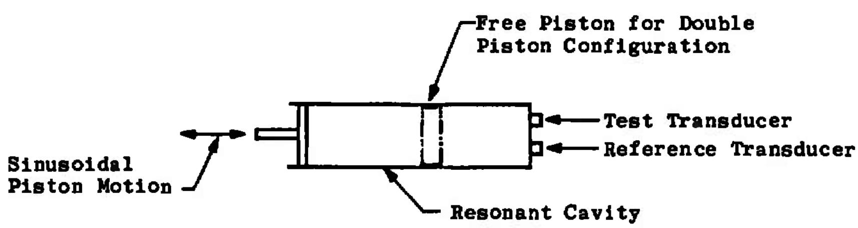
4.2.2.1 Resonant Cavities

A resonant cavity consists of a closed volume to which the transducers are flush mounted or connected and some means of exciting the cavity in one of its resonant modes, usually its lowest frequency one. As mentioned earlier, these devices produce practically pure sinusoidal pressure variations only under special conditions, i.e., low peak-to-peak pressures and low frequencies, and tend to produce sawtooth wave forms at large amplitudes and high frequencies.

Resonant cavities can be driven or excited by a number of schemes. Among the more popular ones are the siren driven (Fig. 94a) and the piston driven (Fig. 94b). A more novel scheme is a rotating gas jet shown in Fig. 94c. The first two operate in a half-wave resonator mode. Thus, the siren speed and the piston frequency must be matched to the resonator length and the speed-of-sound of the gas filling the resonator. Since the wave form of these calibrators is not a pure sinusoid under many conditions of interest, it may be necessary to resort to a Fourier transform analysis (similar to that in Section 4.2.3) to arrive at the desired amplitude and phase data on the transducer being calibrated. Also, for the calibration to be valid, the reference and test transducers must be exposed to the same pressure signal. Trouble may be encountered if the transducer exposure areas at the end of the resonator are not equal in area and shape and/or if the areas are not symmetrical to the resonator pressure field. Mounting symmetry, however, does not guarantee equal pressures because the pressure distribution in the resonator may not be symmetrical. Interchanging transducer positions will indicate such a problem if it does exist.

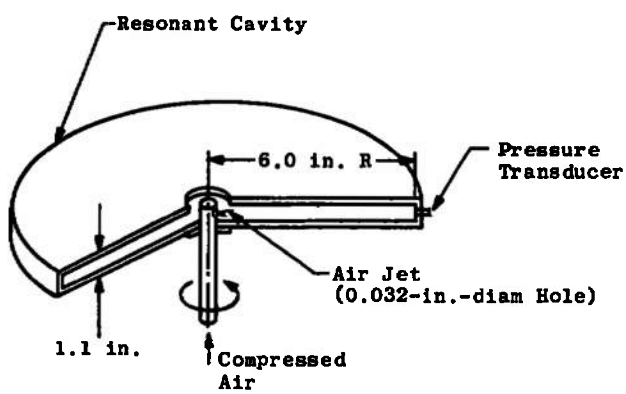


a. Siren Driven



(Horn Driver, Piezoelectric Stack, Electrostatically Driven Diaphragm Crankshaft or Cam Driver)

b. Piston Driven



c. Rotating Air Jet Driven (Cutaway View)

Fig. 94 Resonant Cavity Excitation Schemes

The novel resonator of Fig. 94c (155) consists of a rotating jet of gas at 62.5 psia which excites the cavity in the transverse mode producing a nearly sinusoidal peak-to-peak pressure of 2.5 psi at frequencies less than 700 Hz. A cavity of different radius is required for each discrete frequency desired. Longitudinal resonance is suppressed by the short length of the cavity.

4.2.2.2 Non-Resonant Cavities

Nonresonant cavities operate on the principle of modulating the flow through a chamber or compressing a fixed mass of gas. As indicated in Figs. 95a, b, and c, the flow modulation can either be at the inlet or at the outlet. For the cavities in Figs. 95a and b, the circular perforations will produce near sinusoid pressures while a slotted disk will produce a square wave (157). A sinusoidal cam in Fig. 95c produces a near sinusoid wave shape. The piston-driven cavity, shown in Fig. 95d, is capable of good wave shapes when the peak-to-peak pressure is only a few percent or less of the chamber static pressure. This will usually be the case with all the different driver schemes except crankshaft and cam mechanisms with large strokes. If the change-in-volume time history is known (either inherently from the physical arrangement or measured), then the pressure wave form and amplitude can be calculated, thus giving an absolute calibration. In general, however, a reference transducer of known response is required for nonresonant cavities just as with the resonant cavities. Here, as with the resonant cavities, care must be exercised to make sure both transducers are exposed to the same pressure. The upper frequency limits are determined by the onset of wave motion in the cavities. Small cavities will thus produce higher frequency limits as will an anechoic configuration.

4.2.2.3 Valve Calibrators

A relatively simple low frequency square wave calibrator (143) can be built as shown in Fig. 96. The high frequency limit is set by either the practical upper limit of the shaft speed or resonances in the valve passages. The rotating valve could be replaced with a two-way solenoid valve controlled by a low frequency oscillator. It would seem that one of the solenoid valve step function calibrators (Fig. 89) periodically actuated would serve the purpose.

4.2.2.4 Reciprocity Calibrator

The reciprocity calibration technique is based on measuring the product of the sensitivities of two microphones and then measuring the ratio of the two sensitivities. This can be accomplished with three microphones, two of which must be reversible; the other, the one being calibrated, need not be reversible (158). The product (S_1S_2) and the ratio $\left(\frac{S_1}{S_2}\right)$ of the sensitivities are measured using the apparatus shown in Fig. 97. Microphone 1 must be reversible; i. e., it can act as a receiver or as a transmitter. It is used as a

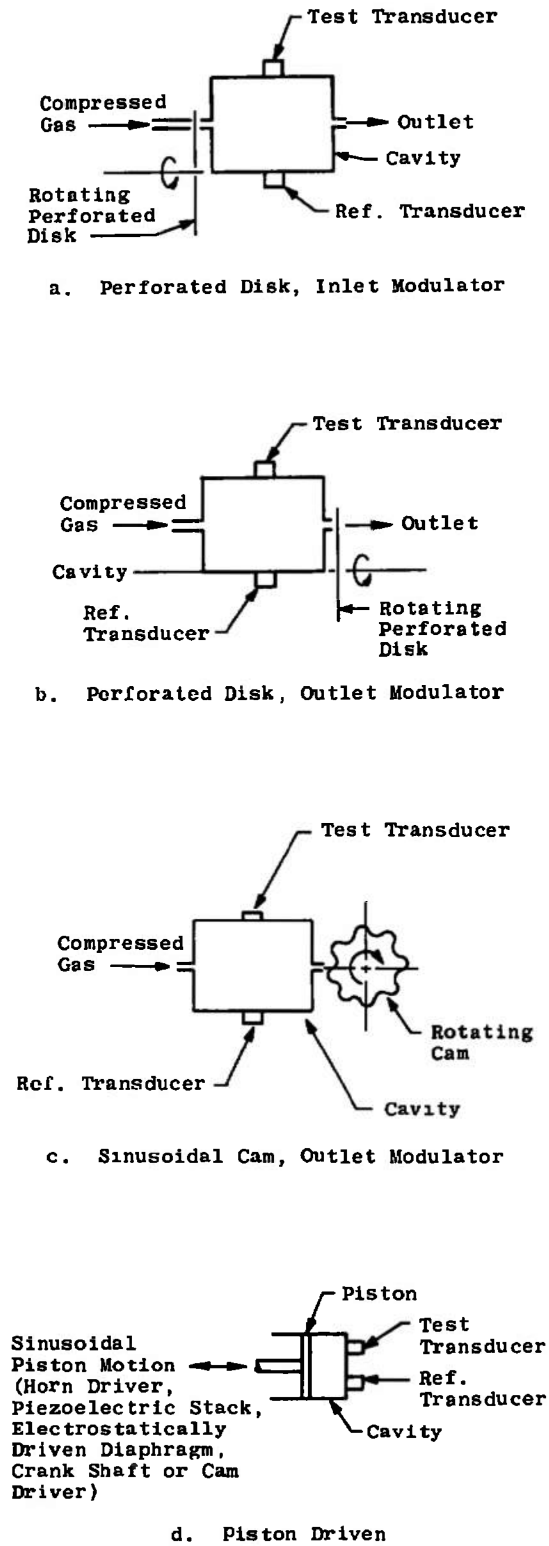


Fig. 95 Nonresonant Cavity Excitation Schemes

transmitter to produce the sinusoidal pressure variation in the coupling cavity of known volume (V), ratio of specific heats (γ), and ambient pressure (p_a). Microphone 2 is the one to be calibrated. It is shown in (159) that

$$\frac{e_2}{e_c} = \frac{S_1 S_2 \beta \gamma p_a C K}{V} \tag{35}$$

The value of the constant K depends on the system of units being used. For the cgs system, $K = 10^7$. By replacing Microphone 1 with a third one which is reversible and alternately measuring the output signal from Microphones 1 and 2 using Microphone 3 as a transmitter, the ratio of the sensitivities can be obtained.

$$\frac{S_1}{S_2} = \frac{e_{2_1}}{e_{2_2}} \tag{36}$$

Then both sensitivities can be derived, although S_2 is the one of primary interest.

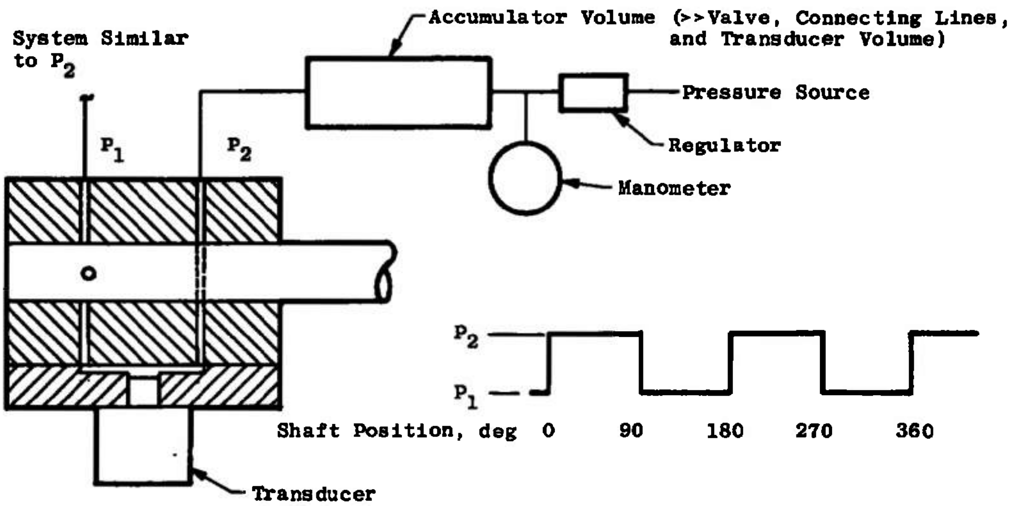


Fig. 96 Rotating Valve Square Wave Generator

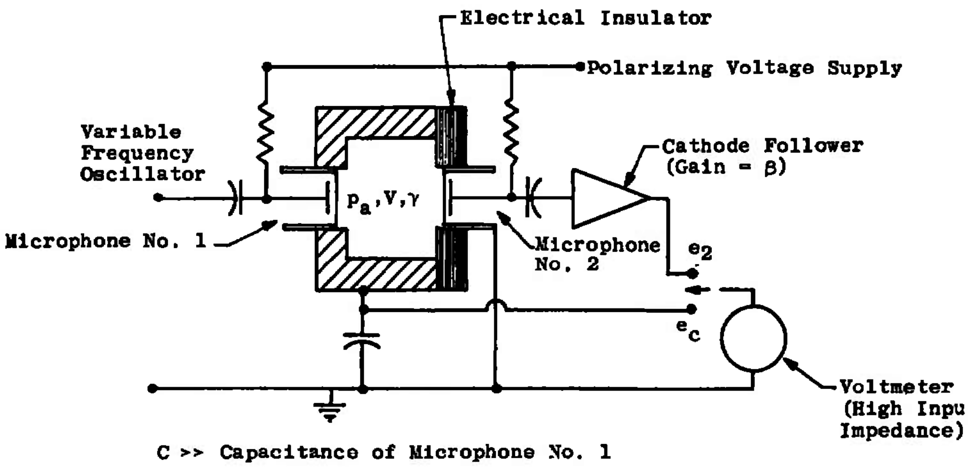


Fig. 97 Schematic for Reciprocity Calibration of Capacitance Microphones

The frequency of applicability is limited at the high end of the spectrum by onset of wave motion in the chamber. The limit can be extended by the use of helium or hydrogen rather than air. One manufacturer (159) of a reciprocity calibrator states an upper frequency limit of 60 kHz for a 0.3-cm^3 coupler filled with hydrogen.

The accuracy of the reciprocity calibration is very good. One experimenter (160) reports ±1 db (~ 12 percent) and a manufacturer (159) of a calibrator states ±0.05 db (~ 0.6 percent) when great care is taken.

Information on the pressure range of the reciprocity calibrators is lacking in the literature. However, it is obvious when the principle of operation is considered that the peak-to-peak pressure can only be a small percentage of the ambient pressure in the coupler.

4.2.2.5 Electrostatic Actuator

Metal diaphragm microphones can be calibrated to an accuracy of around 2 db (~25 percent) with an electrostatic actuator (158). The actuator is a slotted plate which fits close to the microphone diaphragm. A sinusoidal potential is applied between the diaphragm and the plate. Thus, a spatially uniform electrostatic force is applied to the diaphragm in lieu of a uniform "pressure" force. The poor accuracy results from the acoustic coupling between the actuator plate and the diaphragm. This coupling effect is reduced by the slots, but the slots in turn complicate the calculation of the electrostatic force on the diaphragm. The electrostatic actuator calibrator has the advantage of working well at high frequencies where acoustic calibrators are troubled with wave motion in the coupler.

4.2.3 Frequency Domain Data from Time Domain Calibrations

Because of the difficulty in performing frequency domain calibrations, it is sometimes desirable to physically calibrate in the time domain and analyze the data to produce a frequency domain calibration (amplitude and phase data). There are at least two ways this can be accomplished: (1) by the use of Fourier transforms of the time domain data, this gives both amplitude and phase data and (2) by the use of an analog spectrum analyzer which, in general, only produces amplitude data (161). It is convenient to use a step function as the time domain input pressure function because it can be easily produced with a shock tube to such a degree of refinement that it is not necessary to measure it with a reference transducer. It can be assumed for most situations to be a perfect step.

The Fourier transform method involves taking the ratio of the transform of the pressure system output voltage function, e(t), to the transform of the input pressure function p(t).

$$H(\omega) = \frac{E(\omega)}{P(\omega)} = \frac{\frac{1}{2\pi}\int_{-\infty}^{+\infty} e(t)e^{-j\omega t}\,dt}{\frac{1}{2\pi}\int_{-\infty}^{+\infty} p(t)e^{-j\omega t}\,dt} \tag{37}$$

The term $H(\omega)$ is complex and therefore contains both amplitude and phase information. The transforms are most conveniently taken on a digital computer. Therefore, the output voltage function must be digitized by some method. Because of the difficulty of integrating over infinite limits with a digital computer, a square wave output function is synthesized from the actual step response function. This is done by superimposing a negative of the step response on itself after the transient has died out. This is shown in Fig. 98. The synthesis is justified on the assumption that the pressure system is linear. Using the square wave function of period T_D, the frequency domain response or transfer function is

$$H(\omega) = \frac{\frac{1}{2\pi}\int_{0}^{T_D} e(t)\, e^{-j\omega t}\,dt}{\frac{T_D\,\Delta p}{2}\left(\frac{\sin\left(\frac{\omega T_D}{4}\right)}{\frac{\omega T_D}{4}}\right)} \tag{38}$$

The denominator of the above expression is the Fourier transform of a square wave of period T_D. The transfer function is computed only at the points where the denominator of the above equation maximizes, i.e., at odd integer multipliers of the fundamental square wave frequency $2\pi/T_D$. By adjusting the period of the synthesized wave, T_D, within the limits imposed by the durations of the transient and the steady-state portions of the step response, the analysis is not limited to a single fundamental frequency plus its odd harmonics. Errors associated with the digital Fourier transform method are described in (162). The Fourier transforms can also be calculated with an electronic analog computer (163).

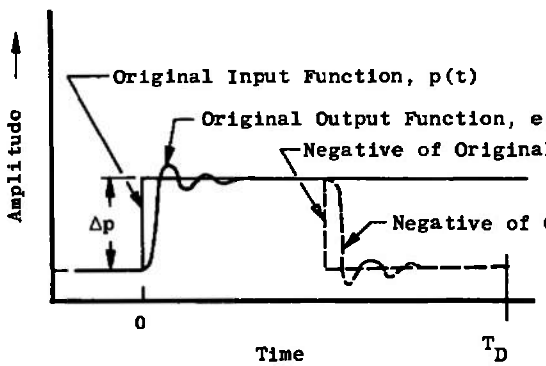


Fig. 98 Synthesized Square Wave Function

The spectrum analyzer method is probably most valuable for locating resonant frequencies in a pressure measuring system. The output function is recorded on magnetic tape or other suitable record/reproduce system and then played back repetitively through a spectrum analyzer.

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13. ABSTRACT

This report was written to give those unacquainted with modern wind tunnel pressure measuring techniques and equipment a broad view of the topic and to provide sufficient references so that additional information may be easily obtained. The material covered is limited to direct pressure measurements, i.e., force per unit area, and does not present techniques that determine pressure through its relationship to other measured parameters. Transducers, signal conditioning, data recording equipment, and static and dynamic calibrations are described.

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